PONTIFICIA UNIVERSIDAD CATOLICA DE CHILE
ESCUELA DE INGENIERIA

IMPLEMENTATION AND CLASSROOM INTEGRATION OF A COLLABORATIVE VIDEOGAME TO SUPPORT TEACHING ELECTROSTATICS CONCEPTUALLY

ALEJANDRO ECHEVERRIA GALVEZ

Thesis submitted to the Office of Research and Graduate Studies in partial fulfillment of the requirements for the Degree of Doctor in Engineering Sciences

Advisor:
MIGUEL NUSSBAUM

Santiago de Chile, June, 2012

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Members of the Committee:

MIGUEL NUSSBAUM
DOMINGO MERY
MATIAS RECABARREN
ALVARO SALINAS
JAN PLASS
CRISTIAN VIAL

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To my beloved family and friends

ACKNOWLEDGEMENTS

Directly or indirectly, there have been dozens people involved in this project, but I would like to start by thanking one, my advisor Miguel Nussbaum, who has been my mentor for the last 6 years. I remember like it was yesterday our conversation that led to my decision to embark on this Ph.D. adventure with him as my advisor. Although throughout the years I have frequently asked myself if this path was the right decision for me, now, looking back at all what I have learned and all the experiences I have had, I am certain that I made the right choice. By working with Miguel during the past years I have learned to love research and acknowledge its tremendous importance in society and I have understood the value of following a grand vision in order to make positive change in the world. His constant support and guidance have been essential in this process, and I cannot thank him enough for always trying to create a “rich and stimulant” environment around me.

I would also like to thank Professor Jan Plass, and all the people at CREATE lab in NYU and at the G4LI, with whom I was lucky to work in my first internship abroad. The experience of working with them was an eye opener in many ways, and it allowed me to become a better researcher and designer, and apply my new skills in my thesis work. Also I would like to thank Sumit Basu, Donald Brinkman and the rest of the people I worked with at MSR during my internship, which was an excellent experience at one of the best research centers of Computer Science in the world.

This thesis would not have been possible if it weren’t for the amazing people that worked with me throughout the different iterations of this project. Especially I would like to thanks Cristián García-Campo, Francisca Gil, Enrique Barrios and Matías Améstica, whose own Masters thesis were interlinked with this project, and who did and incredible work in their different projects. Also I would like to thank Sandra, Sergio, Pedro, Matías and Lucas for their incredible support in the design, experimental and analysis steps of these projects, providing incredible hardwork in order to complete one of the most difficult parts of this research, the classroom experiments. Finally I would also like to thanks every one of the many undergaduates that worked with us during the project, who contributed with effort and insight in the development process.

Another group of people that was essential for this thesis were all the administrators, teachers and students at the different schools were we tested the games. I would like to thank all the people at the Chilean's Eagle School, at the San Francisco of Renca School and at the Navarra School, which helped to make possible this research, and who provided invaluable feedback for the improvement of our project.

I would like to thank my officemates and friends at the DCC, whose company and support during my Ph.D. was very important for arriving to where I am right now. Specially, I would like to thanks Matías, Juan Felipe, Claudio, Vagner and Andrea with whom I shared a lot of good moments during these years. Also I would like to thanks to the many other students, professors, secretaries and administratives in the DCC, who made my extended stay a rich and pleasant experience.

Finally, I would like to thank and dedicate this work to all the members of my family, who have given me so much love and care during all my life. I am forever grateful of my parents who have given me the best education, and who are my role model in life. Thanks to my brothers and sisters, Luz, Nano, Mauricio, Pipa and Seba, who have been great friends and inspiring examples each in their own way; and to their families, my brothers and sisters in law, and my nephews and nieces, whose company and support has been invaluable and a constant source of joy.

This work could not have been possible without the financial support of CONICYT through their Doctoral Student Scholarship.

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ABSTRACT

For the last three decades, researchers and educators have been interested in using videogames for educational purposes. However, videogames have not yet become an everyday tool in education as it was originally imagined. Previous experiences have shown that designing educationally effective and engaging videogames is a very difficult task, and that videogames are not necessarily the right tool to teach every subject. In addition to this, videogames, when used in the classroom, require an explicit pedagogical integration to allow the teacher and students to maximize the usefulness of the tool. There is a need, then, to understand when videogames should be used and how should they be designed and integrated in the classroom.

This thesis focuses on exploring the design and classroom integration of videogames for developing conceptual understanding of basic physic principles, which is one of the learning objectives where there is evidence to suggest that videogames are a better methodology than traditional methods. A design-based research approach is used in this project, developing several iterations of the videogame, experimentally testing them, and gathering insights to improve the next iteration. To explore how to integrate videogames, both at a pedagogical and technological level, this project applies the principles of Computer Supported Collaborative Learning as a basic model for integrating videogames in the classroom. To explore how to design engaging and educationally effective videogames, several principles and theories from the learning sciences research community and from the game design community are applied in order to test their usefulness in this particular context.

Throughout the iterative design process, two technological platforms for deploying collaborative videogames in the classroom were developed, experimentally tested and compared using the same videogame. The effectiveness of each iteration of the videogame was validated through a conceptual survey of physics which was taken by the students before the experience (pre-test) and after the experience (post-test) allowing the observation of possible learning gains. The results of the experiments performed showed that in the last iteration of the videogame (which was tested with 36 students) the average test results increased from 7.36 (std. dev. 2.69) in the pre-test to 12.36 (std. dev. 3.77) in the post-test, which represented a statistically significant learning gain compared to the original version (which was tested with 27 students of the same school) where the average test results increased from 6.11 (std. dev. 2.24) in the pre-test to 10.00 (std. dev. 2.74) in the post-test. Based on the design process and experimental experiences, a methodology for designing and integrating this type of videogames is presented for further validation.

This thesis had the support by the Center for Research on Educational Policy and Practice, Grant CIE01- CONICYT, the Games for Learning Institute, and Microsoft Research.

Members of the Doctoral Thesis Committee:
Miguel Nussbaum
Domingo Mery
Matías Recabarren
Alvaro Salinas
Jan Plass
Cristián Vial
Santiago, June, 2012

PONTIFICIA UNIVERSIDAD CATOLICA DE CHILE
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IMPLEMENTACIÓN E INTEGRACIÓN EN CLASES DE UN JUEGO COLABORATIVO PARA APOYAR LA ENSEÑANZA CONCEPTUAL DE ELECTROSTÁTICA

Tesis enviada a la Dirección de Investigación y Postgrado en cumplimiento parcial de los requisitos para el grado de Doctor en Ciencias de la Ingeniería.

ALEJANDRO ANDRÉS ECHEVERRÍA GÁLVEZ

RESUMEN

En las últimas tres décadas, investigadores y educadores han estado interesados en usar videojuegos para objetivos educacionales. Sin embargo, los videojuegos aún no se han convertido en una herramienta de uso diario en ambientes educativos, como fue imaginado originalmente. Experiencias previas han demostrado que diseñar videojuegos que sean educacionalmente efectivos y entretenidos es una tarea muy difícil, y que los videojuegos no son necesariamente la herramienta adecuada para enseñar todo tópico. Además de esto, cuando los videojuegos se usan como herramienta en la sala de clases, es necesario definir explícitamente como serán integrados pedagógicamente, de manera de permitir que el profesor y los alumnos aprovechen al máximo la herramienta. Existe la necesidad, entonces, de entender cuando deben ser usados los videojuegos, y como deben ser diseñados e integrados en una clase.

Esta tesis se enfoca en explorar el diseño e integración en la sala de clases de un videojuego para el aprendizaje conceptual de principios básicos de física, que es uno de los objetivos de aprendizaje en que la evidencia sugiere que los videojuegos son una mejor herramienta que métodos tradicionales. Una metodología de investigación basada en diseño es usada en este proyecto, desarrollando varias iteraciones de un videojuego, validándolo experimentalmente y obteniendo nuevas ideas en el proceso para mejorar la siguiente iteración. Para explorar la integración del videojuego en la sala de clases a un nivel tecnológico y pedagógico, este proyecto aplica los principios del Aprendizaje Colaborativo Apoyado por Computadores, como modelo básico para integrar el videojuego en la sala de clases. Para explorar cómo diseñar juegos entretenidos y educacionalmente efectivos, varios principios y teorías obtenidos de las comunidades educativas y de diseño de juego son aplicados con el objetivo de entender su utilidad en este contexto.

A través del proceso iterativo de diseño, se desarrollaron y compararon dos plataformas tecnológicas para implementar juegos colaborativos en la sala de clases. La efectividad de cada iteración del juego fue validada ocupando una prueba conceptual de física la cual los alumnos rendían antes de la experiencia (pre-test) y después de ésta (post-test) lo que permitía observer posibles incrementos en el aprendizaje. Los resultados de los experimentos desarrollados mostraron que en la última iteración del juego (probada con 36 alumnos) el promedio del puntaje en la prueba aumentó desde 7.36 (desv. est. 2.69) en el pre-test a 12.36 (dev. est. 3.77) en el post-test, lo que representa una mejora estadísticamente significativa en la ganancia de aprendizaje respect a la primra iteración (probada con 27 alumnos del mismo colegio y edad) el promedio del puntaje en la prueba aumentó de 6.11 (desv. est. 2.24) en el pre-test a 10.00 (desv. est. 2.74) en el post-test. En base al proceso de diseño y a las experiencias experimentales, se presenta una metodología para diseñar e integrar juegos de este tipo, para ser validada con otros temas de física.

Esta tesis contó con el apoyo del Centro de Investigación en Políticas y Prácticas en Educación, CIE01- CONICYT, Games for Learning Institute, y Microsoft Research.

Miembros de la Comisión de Tesis Doctoral

Miguel Nussbaum

Domingo Mery

Matías Recabarren

Alvaro Salinas

Jan Plass

Cristián Vial

Santiago, Junio, 2012

I. INTRODUCTION

The idea of using videogames for educational purposes is as old as videogames themselves. In spite of many years of research on the field, videogames have failed to become an everyday tool in education as it was originally imagined. This failure can be explained by understanding that videogames, like any other technology, are no “silver bullet” and although they have interesting potential, they should be used when their particular affordances are required. This thesis present a design experiment focused on understanding how to design and integrate videogames in the classroom for teaching electrostatics principles conceptually. The focus on conceptual understanding of physics limits the scope of this research to one of the specific learning objectives were simulations and videogames have unique affordances. The methodology of the project is centered on the design, implementation and the classroom integration aspects of the problem, which are explored through an iterative experimental process, resulting in guidelines and methodologies that can be applied for other videogames with similar characteristics.

This chapter starts by presenting a literature review, providing the theoretical background for the thesis and discussion on other studies that cover topics related to those treated in the thesis. Upon this basis, the chapter then describes the motivating factors that prompted the reported research, together with the research hypotheses, research questions, and research objectives. Finally, this chapter presents the limitations of the reported work, and a description of the thesis’ structure.

I.1 Theoretical Background

This thesis is supported by a diverse theoretical background that responds to the interdisciplinary nature of educational game design and development. The following subsections briefly introduce each of the theories comprised in the theoretical framework. In subsection I.1.6 a summary of the theoretical background is presented, indicating the relationships between the different theories involved.

I.1.1 History of Video Games in Education

The idea of using video games for educational purposes has been present since the development of the first successful videogames and the deployment of the first personal computers and game consoles. In the 1980s, researchers studied classic arcade games such as Pac-Man (Bowman, 1982), Arkanoid (Malone & Lepper, 1987) and Asteroids (White, 1984) to understand how players were able to develop expertise on these games and at the same time enjoy the process of doing so, and how could the principles behind them could be applied for learning in serious educational environments.

These initial research initiatives delivered the first theories on why games were engaging learning environments, and how they could be applied in educational context. Malone (1980) proposed that there were three elements that made videogames fun: challenge, fantasy and curiosity, and by incorporating this elements in the design of educational environments, the same level of engagement could be achieved in them. Bowman (1982) used the theory of flow (Csikzentmihalyi, 1988) as his basis to understand why videogames are engaging, suggesting that videogames are designed in such a way that the players are in a constant state of flow while they are playing. The state of flow, as defined by Csikzentmihalyi (1988) is a state of optimal experience, in which the person is completely engaged with the activity he/she is performing, intrinsically motivated by the activity itself to achieve a goal. Bowman suggested that educational environments should be designed in such a way that children could achieve this flow state, and optimize the experience of learning.

In the years after this initial set of landmark research projects, it was expected that games would be incorporated in educational environments and revolutionize the way people learn. However, as with many previous technology-centered "learning revolutions", videogames failed to achieve their promise (Eck, 2006). Many reasons were proposed to explain this failure: educational games were too simplistic in comparison to commercial video games;

the games developed were based on repetitive tasks for drill and practice and became boring; most games were poorly designed, because they were built mainly by academicians and not game designers; and when games were developed by game designers and were entertaining, they did not incorporate meaningful educational aspects (Squire, 2003; Kirriemuir & McFarlane, 2004; Eck, 2006). The term "edutainment" was coined to describe many of these games, and some claimed that the majority of them were a combination of the worst of two worlds: boring games and drill practice learning (Papert, 1998).

In spite of earlier failures, the last decade has seen resurgence in the educational videogames field explained by two main factors. First, videogames have finally become mainstream: instead of appealing only to a subset of society (mainly teenage boys), now the players are of all ages and genders (Eck, 2006). The development and massification of mobile technologies, social networks and new input technologies created an explosion of innovation in the game design space, broadening the type of games developed and acknowledging a diverse spectrum of players (Juul, 2010). The second important factor is that the accumulated evidence of years of research has produced many successful experiences that prove the power of videogames as learning environments, and its advantage over other methodologies in some cases (White, 1984; Squire, Barnett, Grant & Higginbotham, 2004; Barab & Squire, 2004; Dede, 2009; Klopfer, Perry, Squire & Jan, 2005). These successful experiences have started to give light on why games are good learning tools, and what it is necessary to build effective videogames.

The resurged field of educational game design is starting to understand one of the main shortcomings of the initial movement: that videogames are no "silver bullet", and they cannot be used for every learning objective and every subject (Eck, 2006; Kirriemuir & McFarlane, 2004). As with any other teaching technique, videogames are one tool of many and the selection of the right tool depend on the task at hand and the materials one is working (Bransford, 1999). To further the understanding of the field, then, researchers should start by asking when should we use videogames in the first place and after that, how should videogames be designed and integrated in an educational setting to achieve the desired learning outcomes (Eck, 2006)

The research presented in this thesis starts from these general research questions, and aims to provide some initial answers for them in the context of teaching Physics conceptually. Conceptual understanding of complex scientific phenomena is one of the particular affordances that videogames are uniquely suited for (Squire et al, 2004; De Jong & van Joolingen, 1998). The goals of this project are twofold: first, generate some new insights on the game design aspects of conceptual physics games, and second, study how to integrate a videogame in a classroom, considering both pedagogical and technological requirements.

I.1.2 Physics Education

The evidence gathered in the last decades on how people learn, states that one of the fundamental cornerstones required to develop competence in an area of inquiry is the deep understanding of concepts in the context of a conceptual framework (Bransford, 1999). This finding is particularly relevant in physics teaching, were complex systems and models of phenomena are at the heart of the subject, and a good conceptual understanding of these is essential. Based on these facts, many physics educators have argued that it is necessary to shift current ways of teaching focused mainly on mathematical formulae, to a conceptual approach, were the understanding of physical models and systems is the priority (diSessa, 2000; Forbus, 1997; Mazur, 1997).

There is plenty of evidence that suggests that the lecture model used to teach physics is not conducive to achieve deep understanding in students (Mazur, 1997). The development and application of several Concept Inventories, tests designed specifically to assess conceptual understanding, such as the Force Concept Inventory (Hestenes, Wlls & Swackhammer, 1992) and the Conceptual Survey of Electricity and Magnetism (Maloney, Hieggelke & Van Heuvelen, 2001) have shown that current methodologies for physics teaching are not working as well as they should, justifying the need for new approaches (Rosenberg , Lorenzo & Mazur, 2006; Deslauriers, Schelew & Wieman, 2011).

One of these new approaches that have been tried is discovery learning using computer simulations (de Jong & van Joolingen, 1998), i.e. computer programs that contain a model of a system or a process. Simulations based on conceptual models are particularly well suited for scientific discovery learning, because they hold principles, concepts and facts related to the system being simulated, and the learner can infer this characteristics through his/her interaction with the simulation (de Jong & van Joolingen, 1998). In the context of physics, these characteristics of conceptual simulations are particularly well suited to explore real life phenomena making the visual and conceptual models of expert physics accessible to students (Perkins, Adams & Dubson, 2006).

Although using computer simulations has been proven successful in many contexts, there are some difficulties that arise when learners are confronted to this purely discovery learning environments (de Jong & van Joolingen, 1998; Gredler, 2003; Wieman & Perkins, 2006). One of these difficulties is that learners have problems finding new hypotheses and adapting their initial hypotheses based on new data (Chinn & Brewer, 1993). Also, when learners are left by themselves with the simulations, they usually show inefficient experimentation behavior, not using the full range of possibilities of the simulation, or constructing experiments that are not useful (Kuhn, Schauble & Garcia-Mila, 1992).

There is evidence that these problems can be avoided if simulations are designed through some specific principles. One of these principles is model progression, where the simulated model is introduced gradually in order to avoid overwhelming the students with the full complexity of the simulation (de Jong & van Joolingen, 1998). Another important principle is the idea of setting goals, or specific simulation states, that the learners have to achieve through their exploration, in order to direct their interaction with the simulation (White, 1984). The evidence suggests that when these principles are applied to structure the simulation environment, learners perform better in conceptual follow-up tests (de Jong & van Joolingen, 1998).

In addition to the structural principles previously described, an additional requirement for successful simulations is their ability to engage students in the scientific exploration process (de Jong & van Joolingen, 1998; Adams, Reid, LeMaster, McKagan, Perkins, Dubson et al, 2008). Studies made in the design and evaluation of the Physics Education Technology (PhET) project, a large set of online physics simulations (Perkins et al, 2006), have produced a set of requirements needed for creating an engaging simulation (Adams et al, 2008):

- use animation and interactivity to make salient the element where the student should focus,
- make simulations fun to play with, but reduce play element that are distractions
- construct the simulation around little puzzles that the learner must solve,
- create a coherent environment, without unnecessary material.

Simulation based videogames can be a way to both satisfy the structural requirements (de Jong & van Joolingen, 1998; White, 1984) and the engagement requirements (Squire, 2003) necessary to achieve effective learning through simulations. Videogames are essentially incremental, because they must gradually teach the player how to the play (Gee, 2003), and they also have a specific goal to achieve, because they must provide feedback to the player on his/her performance. Well-designed video games are also naturally engaging, because they must motivate the player to keep playing until he/she finishes the game. The combination of these structural and engaging characteristics make videogames ideal for conceptual learning through simulations because they emphasize the process of reflection: unlike a linear process, learning with games follows a cyclical pattern of experience, reflection on that experience, drawing of conclusions based on these reflections, and the formation of a plan for a new action based on those conclusions, before acting once again (Paras & Bizzochi, 2005).

The idea of using simulation-based video games has been successfully applied for developing videogames for the conceptual understanding of physics. Videogames for teaching both Newton's laws of motion (White, 1984) and Maxwell's laws of electromagnetism (Squire et al, 2004), have been developed and tested with successful results, demonstrating that they improve the learning outcomes when compared with other approaches, such as inquiry-based learning (Squire et al, 2004) and unguided discovery learning (White, 1984). However, these previous experiences on physics videogames have left an unanswered question: it is not yet clear how these videogames should be designed, in order to achieve the best learning outcomes and the maximum engagement.

I.1.3 Classroom Integration

Although simulation-based videogames represent an improvement over an unstructured simulation as described previously, simply using a videogame does not ensure that learners will generate the kinds of understandings that educators might desire (Thiagarajan 1998; Squire, 2003). The role of the instructors is essential to maximize the usefulness of videogames as learning tools (Squire, 2003; Habgood & Ainsworth, 2011), by controlling the game-based classroom, fostering collaboration, promoting reflection, and coordinating extension activities (Hawley, Lloyd, Mikulecky, & Duffy 1997). If the instructor is not included in the deployment of videogames, they may feel that the game is a replacement for their participations rather than a tool, which can prompt some instructor to reject them (Kebritchi, 2010).

As with any other technology, to achieve a successful deployment of videogames in a classroom, it is required to "orchestrate" how they will be applied. The concept of orchestration refers to the design and real-time management of multiple classroom activities, various learning processes and numerous teaching actions (Dillenbourg & Jermann, 2010). Classroom orchestration implies not only the design of the tool itself (e.g videogame), but also the design of the complete class experience, including what type of activities will be used when and how will the students interact in each part of the activities, what is the role of instructor thought the different steps, what preparation is required to deploy the technology and what to do in case of a problem (Dillenbourg & Jermann, 2010).

Successful classroom orchestration requires several factors at the teacher, activity and technology level. At the teacher level it is required leadership from the instructor, flexibility to change the learning scenario if it makes sense, and control over the activity and the learning experience as a whole (Dillenbourg & Jermann, 2010). The different activities involved in the learning scenario have to be integrated in a coherent flow and there should be continuity between the elements involved in each one (Dillenbourg & Jermann, 2010). Lastly, the technology used must consider the physical aspects of the real classroom, and all possible problems that may arise, and help the teacher to solve them and be aware of the students state (Dillenbourg & Jermann, 2010).

Although many pedagogical models and instructional strategies could be used to integrate a videogame in the classroom, one pedagogical model that has been already successfully used for this purpose is Computer Supported Collaborative Learning (Infante, Weitz, Reyes, Nussbaum, Gomez, & Radovic, 2010). In Computer Supported Collaborative Learning, or CSCL, students work as a group in a coordinated effort to achieve a specific educational goal (Dillenbourg, 1999). CSCL is more than collaboration around computers with the computer providing a means to coordinate tasks or to simulate problem-solving situations; but rather collaboration through computers, where group members use the computer to structure and define their collaborative endeavors (Haythornwaite, 1999). Studies suggest that when students work collaboratively they get better academic results (Johnson & Johnson 1999), show more participation in group discussions, show a more sophisticated level of expression, put more attention on others and provide more valuable contributions to discussions (Shachar & Sharan, 1994). Working in small groups allows students to observe the needs of others, understand their point of view and find the best way to explain their ideas (Lave & Wenger, 1991; Rogoff & Lave, 1984).

CSCL can be used to orchestrate a class by structuring the activities through a script (Dillenbourg, 2002). A CSCL script is a set of instructions and guidelines that describe for a specific activity how the students are grouped, how they interact and collaborate, how the activity progression is structured and how the teacher mediates the students' interaction (O'Donnell & Dansereau, 1992). CSCL scripts do not cover all the aspects required for a complete orchestration model, but they provide a basic structure that guides the integration of activities in the classroom.

Many technologies have been used to deploy classroom CSCL activities and games: one handheld device per child (Zurita & Nussbaum, 2004); one netbook per child (Nussbaum, Gomez, Mena, Imbarack, Torres, Singer, & Mora, 2010); one phone per child (Echeverría, Nussbaum, Calderón, Bravo, Infante & Vásquez, 2011), one computer for every three children (Infant et al, 2010) and even one computer for the whole classroom (Szewkis, Nussbaum, Denardin, Abalos, Rosen, Caballero, Tagle & Alcoholado, 2010). However, different technological platforms can have different effects on the students that use them (Alvarez, Brown & Nussbaum, 2011), which suggest that it is essential to determine the best technology for the specific activity and context.

The research presented in this thesis explores the specific research question of how to design an instructional collaborative videogame to teach physics conceptually and integrate it in a class, using a CSCL script. A secondary question also explored is how different collaborative technologies used for deploying the same videogame affect the learners' experience.

I.1.4 Videogame Design

In recent years, the field of videogame design has started to mature as a discipline. Many designers and practitioners have produced books and essays (Salen & Zimmerman, 2004; Schell, 2008, Hunicke, LeBlanc & Zubek, 2004) that summarize the general principles of the field, which previously were scattered among many people. Videogame designers have acknowledge that the essence of video game design, has much more in common with traditional game design (boards games, cards games, etc), than with software development (Schell, 2008).

Different designers have proposed a variety of conceptual frameworks for understanding how to analyze and design video games. One of the most recognized of these frameworks is the MDA model (Hunicke et al, 2004), which identifies three main components in games: mechanics, dynamics and aesthetics. This model recognizes that a videogame experience includes both the designer point of view, and how he/she crafts the game, and the player experience while actually playing the game. In the MDA model, mechanics are defined as the systemic interactions created by the designer in the videogame before the play experience; dynamics represent the particular interactions of the player with the system; and aesthetics correspond to the psychological experience of the player while he/she interacts with the game.

Although the MDA model is valuable as a theoretical way of understanding videogames as something more than the designed experience, it doesn't provide a detailed description of the different game elements that are involved in the play experience (Cook, 2007). One way of describing the game elements is the "elemental game tetrad" defined by Schell (2008), which divides all elements into four categories: mechanics, story, aesthetics and technology. The mechanics of a game describes its procedures and rules, defining how players can achieve the game's goal. They are the key elements differentiating games from other kinds of media in that they give the former their interactivity (Schell, 2008). The story describes the sequence of events that unfolds during a game. It can be very simple and linear, or highly complex and branching. The level of storytelling will vary, ranging from games that are completely abstract with very low narrative elements to story-driven games that more closely resemble interactive movies (Schell, 2008). The aesthetics, as defined by Schell (2008), describes how the game looks (graphic design, colors) and sounds (music, sound effects). They define its general tone, which will affect the feelings a player experiences when playing (Schell, 2008). Finally, the technology defines the materials and interactions that make playing the game possible, and includes such elements as input devices and displays. It enables the game to do certain things while banning it from doing certain others (Schell, 2008).

The objective of these and others frameworks is to help characterize a videogame in order to enhance the engagement and motivation of the player during the gameplay experience, so he/she keeps playing the videogame. This ability to become a “motivational engine” that pushes the player to keep playing is the main factor of why videogames have been considered as an educational tool. However, not all researchers entirely agree on the source of this motivation. Some attribute the compelling nature of games to their narrative or fantastic context (Dickey, 2006; Fisch, 2005; Waraich, 2004) while others find motivation is linked to goals and rewards within the game itself or intrinsic to the act of playing (Amory, Naicker, Vincent, & Adams, 1999; Denis & Jouvelot, 2005; Jennings, 2001).

Researchers that postulate that the narrative of a videogame is the main source of engagement base their claims on the idea that curiosity and fantasy are the essential sources of engagement in videogames (Malone, 1980; Malone & Lepper, 1987; Garris, Ahlers & Driskell, 2002). Malone and Lepper (1987) define fantasy as an environment that “evokes mental images of physical or social situations not actually present”. Garris et al. (2002) assert that including “imaginary or fantasy context, themes, or characters” and providing “optimal level of informational complexity” can make computer games motivational. According to these researchers, in an educational videogame the fantasy context can be either intrinsic/endogenous or extrinsic/exogenous to the game content (Rieber, 1996). In endogenous fantasy, the content to be learned is embedded in the fantasy context, i.e., the skill to be learned and the fantasy are related to each other. In exogenous fantasy, the relationship between the content of the study and the fantasy is purely arbitrary. These researchers claim that a successful educational videogame is one with an endogenous fantasy context (Rieber, 1996).

Although the idea of endogenous fantasy as an essential component was maintained for many years as one of the cornerstone elements in the educational game design field, researchers have started to challenge its validity. The central critique to the concept of endogenous fantasy is that such fantasy contexts are often purely arbitrary and could be swapped for another so long as the basic mechanics of the game are not altered (Habgood, Ainsworth, & Benford, 2005). For these authors, the essence of a videogame is not in the fantasy element and how well it is integrated, but in the game mechanics which define the different game genres and the types of flow experiences they produce. They postulate that it is through the core mechanics of a game that many of the motivational effects of challenge, control, cooperation, and competition would be realized (Habgood, Ainsworth, & Benford, 2005).

The idea of mechanics as the core source of engagement in games has also been postulated by non-educational video game designers. Koster (2005) postulates that the essential source of engagement or fun in games is learning how to solve interesting challenge through interacting with the different game mechanics. The player can be understood as entity that is driven, consciously or subconsciously, to learn new skills high in perceived value, gaining pleasure from successfully acquiring skills (Cook, 2007). Cook (2007) describes that fun and engagement: *"is derived from the act of mastering knowledge, skills and tools. When you learn something new, when you understand it so fully you can use that knowledge to manipulate your environment for the better, you experience joy"*.

The debate of whether it is through fantasy or mechanics that videogames create engagement is crucial in the context of educational videogame design. If fantasy is the essential component of engagement, designers should focus on creating stories that relate to the educational content. If mechanics is the essential component, designers should focus on integrating the educational interactions with challenging game mechanics. It also may be the case that both are relevant, or that the source of engagement may vary depending on the type of game.

The research presented in this thesis analyzes these different points of view on what makes videogames engaging by exploring the specific question of whether a fantasy context improves engagement of students playing a videogame for the conceptual understanding of physics.

I.1.5 Design-Based Research

Much of the research in the field of educational games has focused on comparing game playing to lecturing, which is often inappropriate because they are different pedagogical techniques which are suited for different types of learning experiences (Squire, 2003). In the case of teaching physics conceptually, there is enough evidence that supports that lectures are not the best methodology (Mazur, 1997), and that discovery learning through unstructured simulations is also not enough (de Jong & van Joolingen, 1998). This suggests that instead of asking research questions focused on comparing different methodologies, it is more useful to ask how to best design a specific methodology, and apply and iterative strategy that elucidates some questions, but also creates new ones regarding not only the effectiveness of the methodology, but also additional implications relevant to a real educational environment (Reeves, 2008).

Many researchers in the learning sciences field have started using design-based research (Brown, 1992) as an alternative approach to the traditional predictive research methodology (Reeves, 2008; The Design-Based Research Collective, 2003, Barab & Squire, 2004, Cobb, 2003). Design-based research or design experiments, as they are also called, use case study techniques to understand and iteratively improve a design. The research cycle of design-based research differs in several aspects to the traditional predictive research (Figure I.1). Predictive research is centered on the hypotheses-experiment-theory cycle, which eventually may or may not lead to a future application of the new methodology. Design-based research uses an iterative approach that starts with a problem, proposes a possible solution, and tests this solution in real educational settings, collaborating directly with practitioners and analyzing in a multidimensional way what was the impact of the intervention. After each intervention, the design is refined based on the evidence gathered, until a final design is delivered. A reflection on the complete process allows the creation of theories and lessons learned, that although may not necessarily yield generalizable knowledge, but they can serve to inspire other designers in similar situations (Bracey 1992).

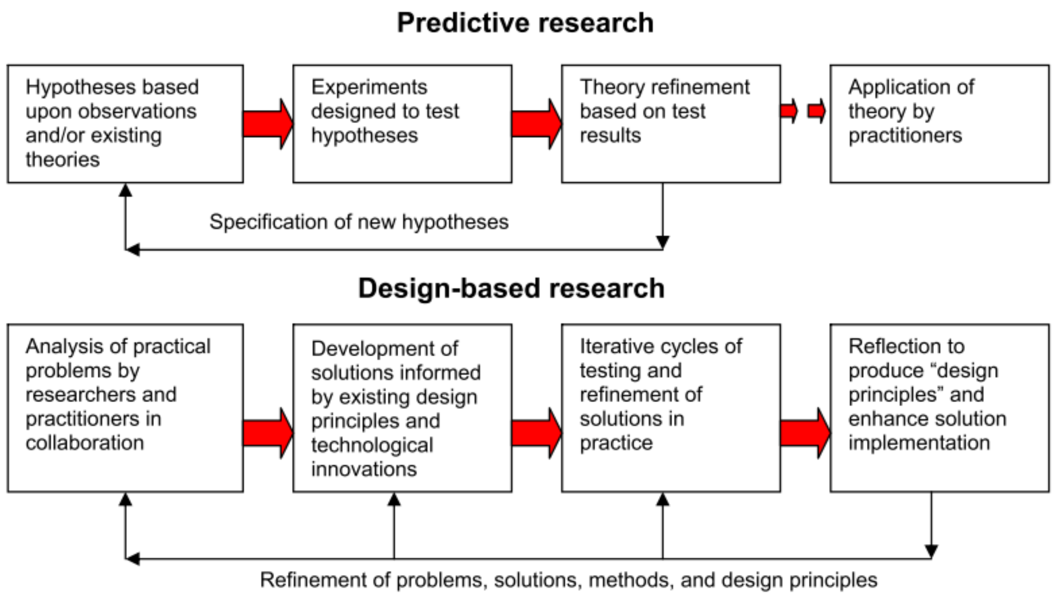

Figure I.1. The Design-based research methodology uses an iterative approach that starts with a problem, proposes a possible solution, and tests this solution in real educational settings, which differs from the traditional Predictive research methodology.

A succesful design-based research experiment must include several features. First, the purpose of the experiment must be to develop theories about the process and the means required to support learning in a specific context (Cobb, 2003). Second, the experiment must be interventionist: it has to be applied in a real setting, and not in a lab (Barab & Squire, 2004). A third essential feature is that design experiments must explicitly test both the initial experimenter hypotheses and theories developed during the process, meaning that the researchers have to be willing to recognize that their hypotheses and theories can be wrong, and foster the emergence of alternative pathways that are discovered during the iterative process (Cobb, 2003). A fourth characteristic is the iterative nature of the process: a design experiment must include several interventions that allow the researchers to observe changes, and generate new theories (Reeves, 2006). The final important feature of a design experiment is humility: the contextual nature of this type of research implies a domain-specificity of any theory produced, which should try to avoid general philosofical claims that are not supported by the specific evidence gathered (Cobb, 2003).

The research presented in this thesis uses the design-based research approach to explore the game design and classroom integration aspects of the implementation of an instructional videogame to teach physics conceptually. By applying this methodology, this thesis explores if a design-based research methodology can be used to increase the effectiveness of a videogame through the development of several iterations.

I.1.6 Theoretical Background Summary

The design-based research process of this thesis is described in Figure I.2, showing the relationship between the different theoretical backgrounds presented. The methodology starts from Physics education, were researchers have acknowledged a need to modify current approaches of teaching to new ones that focus on conceptual understanding (Mazur, 1997; Wieman & Perkins, 2006, di Sessa, 1998), such as structured simulations or videogames (de Jong & van Joolingen, 1998). The specific problem of study of this project is how to design and integrate structured videogames for teaching physics conceptually in the classroom. To confront the problem, we based our research in existing design principles for classroom learning, that propose the idea of Classroom Orchestration as a way of integrating new technological practices into the classroom (Dillenbourg & Jermann, 2010). From a pedagogical perspective we chose the Computer Supported Collaborative Learning model (Dillenbourg, 1999) which when structured using scripts, has been successfully deployed for orchestrating classroom-based games (Infante et al, 2010). The solutions implemented apply principles of videogame design (Schell, 2008; Cook, 2007; Habgood & Ainsworth, 2011), and collaborative technologies, to develop different game technologies and test one videogame for teaching physics conceptually, proposing methodologies for the design and classroom integration of this type of games. Finally the designed videogame is iteratively tested by assessing the increase of conceptual understanding of students through a modified version of the Conceptual Survey of Electromagnetism (Maloney et al, 2001; Appendix A), comparing the results for different versions of the videogame.

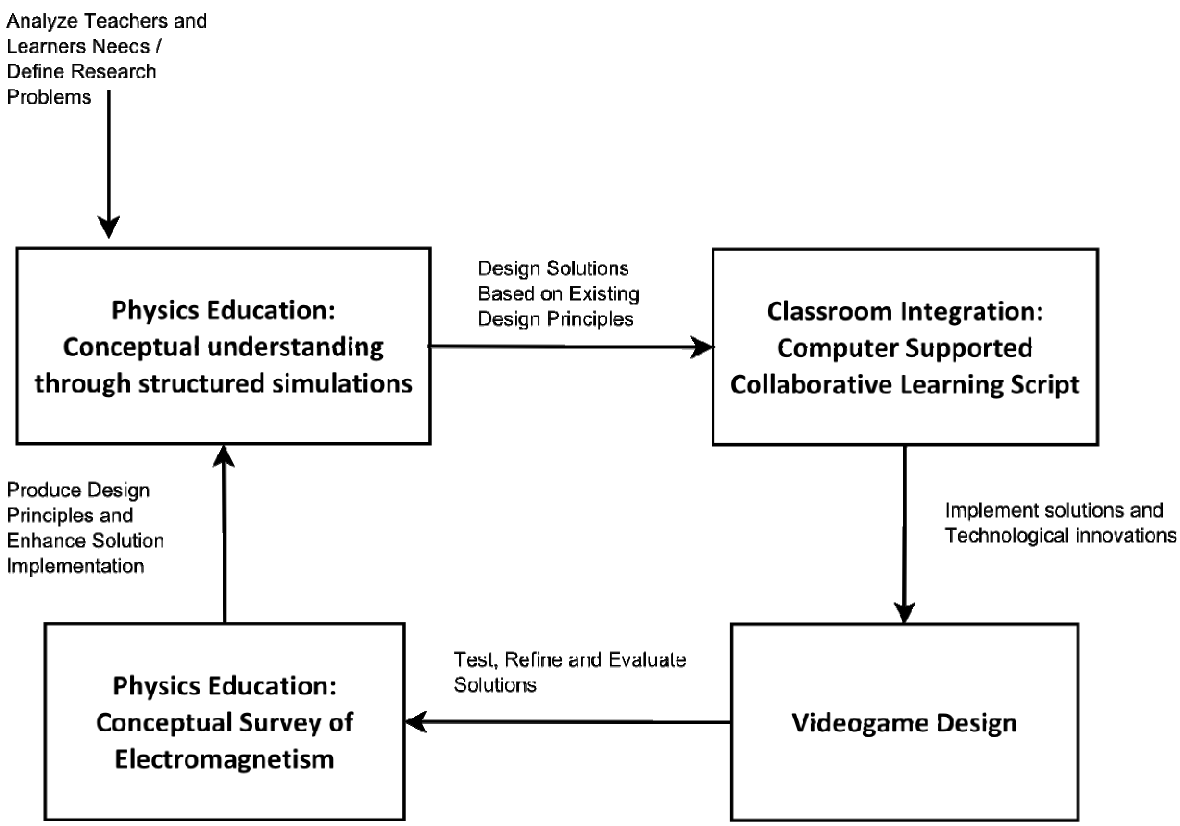

Figure I.2. The design-based research iterative process of this thesis starts from the problem of understanding how to design structured simulations to teach physics concepts in the classroom, then a videogame-based class is developed based on CSCL and videogame design principles, then the effectiveness of the intervention is evaluated with a conceptual survey and that information is used for the next iteration.

I.2 Research Hypotheses

The research hypotheses of this thesis are the following:

1. It is possible to design an instructional collaborative videogame to teach physics conceptually and integrate it in a class through a CSCL script using different technological platforms, achieving significant increase in the conceptual understanding of physics in students comparing their results in a pre-test before the experience with a post-test after the experience.

2. A design-based research methodology can facilitate developing educational videogames to teach physics conceptually, producing significantly better learning gains in the final iteration of the videogame compared to the first one.

3. The technological platform used to deploy the same physics videogame in the classroom will have an impact on the learning gains of students.

4. A physics videogame designed with a narrative structure and fantasy elements will produce more engagement on students than a videogame with no fantasy but there will not be differences in learning gains.

I.3 Research Questions

In relation to the hypotheses previously enunciated, the research reported in this thesis has been driven by the following research questions:

1. Is it possible to design an instructional collaborative videogame to teach physics conceptually and integrate it in a class through a CSCL script using different

technological platforms that increase the conceptual understanding of physics in students?

2. Can a design-based research methodology facilitate developing educational videogames to teach physics conceptually and produce significantly better learning gains in the final iteration of the videogame compared to the first one?

3. Does the usage of different technological platforms for the deployment of the same videogame to teach physics has an impact on the learning gains of students?

4. Will a physics videogame designed with a narrative structure and fantasy elements produce more engagement on students than a videogame with no fantasy?

I.4 Objectives

The specific research objectives proposed in this thesis are the following:

1. Iteratively design a collaborative videogame and a CSCL script to teach physics conceptually, centered on the concepts of Coulomb's Law and the Law of Linear Superposition of Forces, using the design-based research methodology.

2. Develop and test in a real classroom setting two different technological platforms for the deployment of collaborative videogames in the classroom: one using augmented reality technology with low cost mobile devices and the other one using a Singe Display Groupware with multiple mice.

3. Conduct a comparative evaluation of the two different technological platforms developed for classroom collaborative videogames for determining which version produces the higher learning gains in the case of physics videogame.

4. Conduct a comparative evaluation of fantasy and non-fantasy based collaborative physics videogames for determining which version produces the higher levels of engagement.

5. Propose a methodology for the design of other videogames for the conceptual understanding of physics, based in the experiences gained during the complete research project.

I.5 Results

The research done for this thesis produced several results including software implementations, experimental results and design methodologies, which are listed below:

1. The design of collaborative videogame to teach electrostatics conceptually and a CSCL script to integrate it in the classroom that significantly increases the learning gains of students.

2. Two technological platforms for the deployment of collaborative videogames in the classroom: one based on augmented reality and mobile devices, the other one based on Single Display Groupware and multiple mice.

3. There was no significant difference in the learning gains of students who used the augmented reality platform compared to the ones who did not: in the augmented reality videogame (which was tested with 27 students) the average test results increased from 3.51 (std. dev. 2.04) in the pre-test to 6.37 (std. dev. 2.89) in the post-test; in the multiple-mice videogame (which was tested with 18 students of the same school) where the average test results increased from 4.27 (std. dev. 1.74) in the pre-test to 6.22 (std. dev. 3.13) in the post-test.

4. A methodology to help the design of videogames for the conceptual understanding of physics.

5. There was no significant difference in engagement of students who played the fantasy and non-fantasy version of the videogame.

6. The final iteration of the videogame produced significantly better learning gains than the first iteration: in the last iteration of the videogame (which was tested with 36 students) the average test results increased from 7.36 (std. dev. 2.69) in the pre-test to 12.36 (std. dev. 3.77) in the post-test, which represented a statistically significant learning gain compared to the original version (which was tested with 27 students of the same school) where the average test results increased from 6.11 (std. dev. 2.24) in the pre-test to 10.00 (std. dev. 2.74) in the post-test.

I.6 Research Limitations

As it is with most design-based research projects, it is very hard to generalize the results of this thesis beyond the specific context and constrains associated to this project (Barab & Squire, 2004). All the experiments in this project were carried out with Chilean students of mid-to-low level of income with ages ranging from 16 to 18, something that limits the experimental results to this population. The physics videogame developed was designed for specific learning objectives related mainly to Electrostatics, so it is also hard to generalize the experimental results and the proposed methodology to other videogames, even within the topic of physics.

Regarding the classroom orchestration of the videogame, the project presents important short-comings that limit its validity. The most important of these short-comings is that in all the experiments conducted the teacher role was performed by one of the researchers. This decision was made both for experimental and practical reasons. Experimentally, we wanted to isolate the possible teacher effect, considering that the samples were small and each iteration was tested only once. By having the same researcher acting as a teacher during the whole design-research process, we were able to eliminate this possible confounding variable. Several practical reasons were also considered for making this choice. First, one of the important aspects of the project was to test innovative technological platforms for the deployment of classroom games. Because these platforms, in particular the augmented reality one, were created for the project, they were in a very immature state when the experiments were performed, and they required specific technical knowledge to manage possible problems. It was decided, then, that it was preferable to combine the roles of teacher and technical specialist in only one person, to facilitate the overall management of the experience. Another important practical reason was the fact that the activities were used only during one hour session, and during the project there would have been at least three teachers involved. Training three teachers to learn how to use and manage the platform and the videogame to apply them for only one hour was not feasible.

Another characteristic of the project that limits its validity is that all the videogame classes were carried out with only nine students simultaneously, because of the experimental nature of the platforms. The platforms and videogame, then, were not validated in a completely real school setting, only in a scale-down version of it. In summary it can be stated that this research project did not implement a complete orchestration model (which should include every realistic aspect of a classroom intervention); instead it implemented a simplified integration structure which allowed a semi-realistic testing of the different hypotheses.

The goal of this project was not to create a ready-to-use platform and videogame that could be deployed in a classroom setting in the short term. The time horizon of this project was long term and the main goal was to gain some knowledge on the design process of creating this type of videogame-centered classrooms. Although the results are not generalizable, they can give some initial insights to future researchers on what elements should be considered and analyzed when videogames are used as a learning tool.

I.7 Thesis Outline

This thesis is structured in three self-contained chapters, each of them being a paper published in a refereed journal. The listing of the subsequent chapters of this thesis is as follows:

II. A framework for the design and integration of collaborative games inside the classroom
Echeverria, A., Garcia-Campo, C., Nussbaum, M., Gil, F., Villalta, M., Améstica, M. & Echeverría, S.
Computers & Education, 57 (1), pp 1127-1136, 2011, Elsevier.

III. Exploring different technological platforms for supporting co-located collaborative games in the classroom
Echeverría, A., Améstica, M., Gil, F., Nussbaum, M., Barrios, E. & Leclerc, S.
Computers in Human Behavior, 28 (4), pp 1170-1177, 2012, Elsevier.

IV. The Atomic Intrinsic Integration Approach: A structured methodology for the design of games for the conceptual understanding of physics
Echeverría, A., Barrios, E., Nussbaum, M., Améstica, M. & Leclerc, S.
Computers & Education, *59(2), pp 806-816, 2012, Elsevier.*

Chapter II consists of the paper: "A framework for the design and integration of collaborative games inside the classroom." This chapter reports on the first iteration of the videogame, were a general framework for integrating and designing classroom videogames was proposed. The framework gives a general guide on how to combine educational aspects such as learning objectives defined by Bloom's revised taxonomy and the instructional strategy used (in this case CSCL), with the core videogame elements as defined by Schell (2008): mechanics, story, aesthetics and technology. This general framework was used to guide the design of the first version of the videogame to teach electrostatics conceptually. An experimental study was performed with the videogame to validate it as an effective learning tool, by assessing students learning gains with a modified version of the Electromagnetism Concept Inventory (Maloney et al, 2001; Appendix A) that was delivered before the experience (pre-test) and after the experience (post-test).

Chapter III consists of the paper: “Exploring different technological platforms for supporting co-located collaborative games in the classroom”. This chapter reports the design and implementation of two technological platforms for deploying collaborative videogames in the classroom, one using augmented reality and mobile devices and the other using Singe Display Groupware and multiple mice. It also details how the class using the electrostatics videogame was orchestrated in this environment. A comparative experimental study is presented, comparing the learning gains of students that participated in the class with each technology applying a modified version of the Electromagnetism Concept Inventory (Maloney et al, 2001; Appendix A) that was delivered before the experience (pre-test) and after the experience (post-test).

Chapter IV consists of the paper: “The Atomic Intrinsic Integration Approach: A structured methodology for the design of games for the conceptual understanding of physics”. This chapter reports on the methodology used to improve the educational effectiveness and engagement of the electrostatic videogame, based on game design theories and the original experience. An experimental study was performed on the same school and level as the original experiment described in Chapter II, and a comparative analysis of the results of both versions is presented comparing the learning gains of students that participated in the class with each technology applying a modified version of the Electromagnetism Concept Inventory (Maloney et al, 2001; Appendix A) that was delivered before the experience (pre-test) and after the experience (post-test).. In addition to these, an additional experimental study is presented, comparing a fantasy and non-fantasy version of the redesigned videogames, analyzing both the engagement of students and their learning gains. To asses the engagement of students, the Game Experience

Questionnaire was used (IJsselsteijn et al, 2008; Appendix B) which measures seven dimensions: *competence*, *immersion*, *flow*, *tension*, *challenge*, *negative affect* and *positive affect.*

I.8 Thesis Structure

This thesis is structured around the research objectives mentioned previously: (1) the iterative design of a collaborative videogame and a CSCL script to teach physics conceptually, centered on the concepts of Coulomb's Law and the Law of, (2) the development and deployment of two technological platforms for implementing collaborative videogames in the classroom: one using augmented reality technology with low cost mobile devices and the other one using a Singe Display Groupware with multiple mice, (3) a proposed a methodology for the design of other videogames for the conceptual understanding of physics, based in the experiences gained during the complete research project., (4) a comparative evaluation of the two technological platforms for classroom collaborative videogames for determining which version produces the higher learning gains in the case of physics videogame., and (5) a comparative evaluation of fantasy and non-fantasy based collaborative physics videogames for determining which version produces the higher levels of engagement. The thesis' structure is summarized on Table I.1.

Figure I.3 shows the connection among the hypotheses, research questions, objectives, papers and obtained results. The relationship between hypotheses, research questions, objectives and papers was described in Chapter I of this document. Next, the relationship between papers and the obtained results is analyzed.

Table I.1. Summary table detailing the hypotheses, questions, objectives, papers and results presented in this thesis.

Hypotheses	
H1	It is possible to design an instructional collaborative videogame to teach physics conceptually and integrate it in a class through a CSCL script using different technological platforms, achieving significant increase in the conceptual understanding of physics in students.
H2	A design-based research methodology can facilitate developing educational videogames to teach physics conceptually, producing significantly better learning gains in the final iteration of the videogame compared to the first one.
H3	Using different technological platforms for the deployment of videogames to teach physics will have an impact on the learning gains of students.
H4	A physics videogame designed with a narrative structure and fantasy elements will produce more engagement on students than a videogame with no fantasy.
Research Questions	
Q1	Is it possible to design an instructional collaborative videogame to teach physics conceptually and integrate it in a class through a CSCL script using different technological platforms that increase the conceptual understanding of physics in students?
Q2	Can a design-based research methodology facilitate developing educational videogames to teach physics conceptually and produce significantly better learning gains in the final iteration of the videogame compared to the first one?
Q3	Does the usage of different technological platforms for the deployment of videogames to teach physics has an impact on the learning gains of students?
Q4	Will a physics videogame designed with a narrative structure and fantasy elements produce more engagement on students than a videogame with no fantasy?
Objectives	
O1	Iteratively design a collaborative videogame to teach physics conceptually and a

	CSCL script, centered on the concepts of Coulomb's Law and the Law of Linear Superposition of Forces, using the design-based research methodology.
O2	Develop and deploy it in a real classroom setting two different technological platforms for the deployment of collaborative videogames in the classroom: one using augmented reality technology with low cost mobile devices and the other one using a Singe Display Groupware with multiple mice.
O3	Propose a methodology for the design of other videogames for the conceptual understanding of physics, based in the experiences gained during the complete research project.
O4	Conduct a comparative evaluation of the two different technological platforms developed for classroom collaborative videogames for determining which version produces the higher learning gains in the case of physics videogame.
O5	Conduct a comparative evaluation of fantasy and non-fantasy based collaborative physics videogames for determining which version produces the higher levels of engagement.
Papers	
P1	A framework for the design and integration of collaborative games inside the classroom
P2	Exploring different technological platforms for supporting co-located collaborative games in the classroom
P3	The Atomic Intrinsic Integration Approach: A structured methodology for the design of games for the conceptual understanding of physics
Results	
R1	The design of collaborative videogame to teach electrostatics conceptually and a CSCL script to integrate it in the classroom that significantly increases the learning gains of students.
R2	Two technological platforms for the deployment of collaborative videogames in the classroom: one based on augmented reality and mobile devices, the other one based on Single Display Groupware and multiple mice.

R3	There was no significant difference in the learning gains of students who used the augmented reality platform compared to the ones who did not, but the platform based on augmented reality created gender differences in the results, where boys outperformed girls.
R4	A methodology to help the design of videogames for the conceptual understanding of physics.
R5	There was no significant difference in engagement of students who played the fantasy and non-fantasy version of the videogame.
R6	The final iteration of the videogame produced significantly better learning gains than the first iteration.

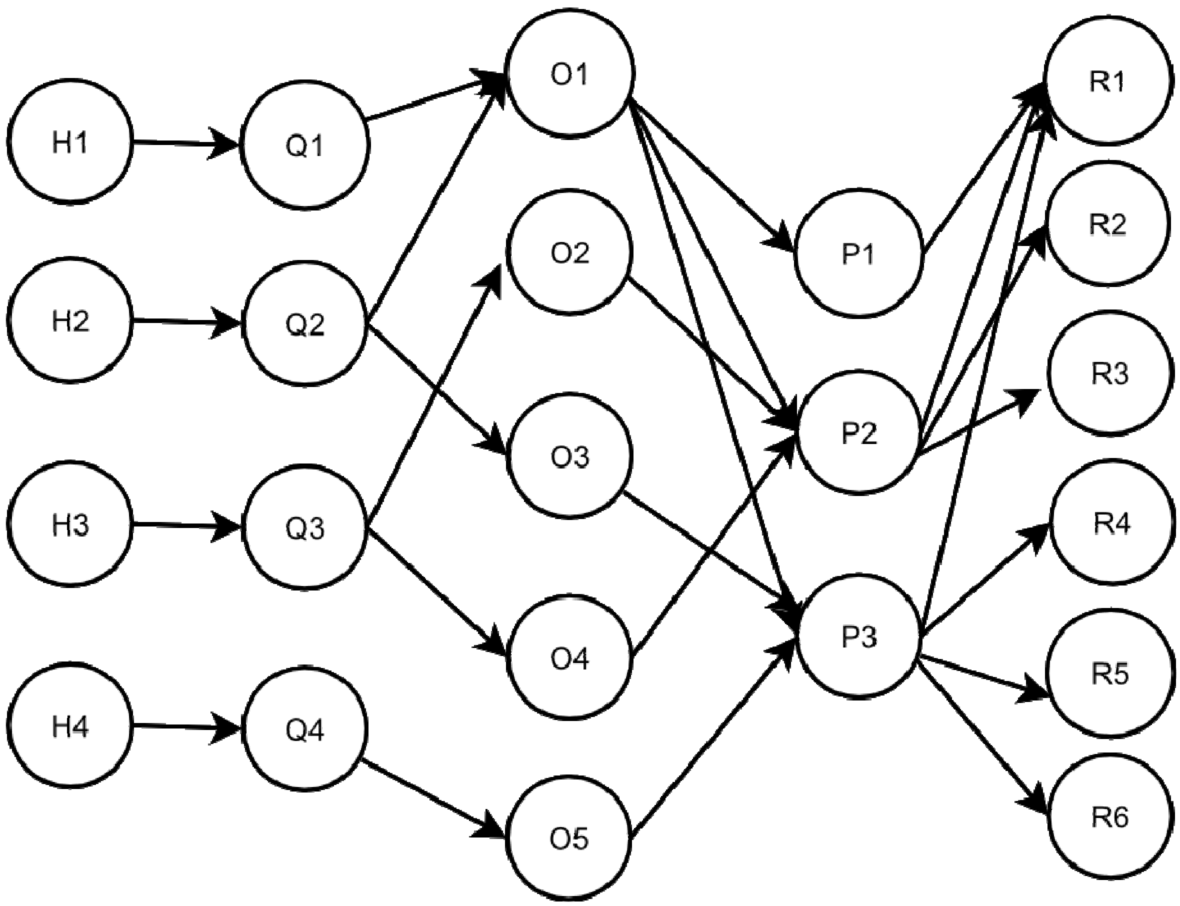

Figure I.3. Summary diagram presenting the relationship between the hypotheses, questions, objectives, papers and results presented in this thesis.

Responding to hypothesis H1, i.e., *"It is possible to design an instructional collaborative videogame to teach physics conceptually and integrate it in a class through a CSCL script using different technological platforms, achieving significant increase in the conceptual understanding of physics in students."*, and the related research question Q1 and objective O1, paper P1 details the design and classroom integration of a videogame to teach electrostatics conceptually and an experimental study that shows a significant increase in the learning gains of students (result R1). In response to hypothesis H2, i.e., *"A* *design-based research methodology can facilitate developing educational videogames to teach physics conceptually, producing significantly better learning gains in the final iteration of the videogame compared to the first one"*, and the linked research question Q2 and research objective O1, paper P1 also presents the first iteration of the videogame developed using the design-based research methodology, which serves as a baseline for comparing future iterations (result R6).

Considering hypothesis H1, and the related research question Q1 and objective O1, paper P2 details the classroom integration of the previously designed videogame using different technological platforms and an experimental study that shows a significant increase in the learning gains of students with this new platforms (result R1). In response to hypothesis H2, and the linked research question Q2 and research objective O1, paper P2 presents the second iteration of the videogame developed using the design-based research methodology, which serves as an intermediary step for the design of the final version of the game (result R6). Regarding hypothesis H3, i.e., *"Using different technological platforms for the deployment of videogames to teach physics will have an impact on the learning gains of students."* and the linked research question Q3 and research objectives O2 and O4, paper P2 describes two technological platforms for deploying collaborative videogames (result R2), and an experimental study comparing the learning gains of students who used each platform (result R3).

In relation with hypothesis H1, paper P3 details a new version of the videogame, with re-designed elements, and an experimental study that shows a significant increase in the learning gains of students with the new design (result R1). Regarding hypothesis H2 and the linked research question Q2 and research objectives O1 and O3, paper P3 presents the final iteration of the videogame developed using the design-based research methodology, a comparative analysis with original version that shows a significant increase in the learning gains of the students who played the final version (result R6) and the methodology used to redesign the videogame (result R4). Finally considering hypothesis H4, i.e., *"A physics videogame designed with a narrative structure and fantasy* *elements will produce more engagement on students than a videogame with no fantasy"* paper P3 presents an experimental study of two versions of the videogame, one with fantasy elements and one without, showing that there were no significant differences in the engagement of students in both groups (results R5).

To conclude, each of the four research questions hereby presented have been answered. Firstly, the experience designing and integrating the different versions of the videogame and validating experimentally their educational effectiveness, supports that it is indeed possible to design an instructional collaborative videogame to teach physics conceptually and integrate it in a class through CSCL script, using different technological platforms, achieving significant increase in the conceptual understanding of physics in students. In addition, the design-based process facilitated the design and integration of the videogame, helping to develop a more effective version in the final iteration. Secondly, the comparative analysis of the two versions of the game with the two platforms implemented showed no difference in learning gains when all students were considered, but also showed an unexpected gender difference that negatively affected the girls that used the augmented reality platform. Finally, the comparative analysis of the fantasy and non-fantasy versions of the game, showed no significant differences in the levels of engagement, contradicting the hypothesis based on previous literature that the fantasy version should increase the level of engagement.

II. A FRAMEWORK FOR THE DESIGN AND INTEGRATION OF COLLABORATIVE CLASSROOM GAMES

Abstract. The progress registered in the use of video games as educational tools has not yet been successfully transferred to the classroom. In an attempt to close this gap, a framework was developed that assists in the design and classroom integration of educational games. The framework addresses both the educational dimension and the ludic dimension. The educational dimension employs Bloom's revised taxonomy to define learning objectives and applies the classroom multiplayer presential game (CMPG) pedagogical model while the ludic dimension determines the gaming elements subject to constraints imposed by the educational dimension. With a view to validating the framework, a game for teaching electrostatics was designed and experimentally implemented in a classroom context. An evaluation based on pre/post testing found that the game increased the average number of correct answers by students participating in the experiment from 6.11 to 10.00, a result found to be statistically significant. Thus validated, the framework offers a promising basis for further exploration through the development of other games and fine-tuning of its components.

1. Introduction

The use of video games as educational tools is slowly becoming an accepted practice in learning environments (Van Eck, 2006). There is growing recognition that several principles underlying these games can be beneficial to the learner: they give immediate feedback, facilitate transfer of concepts from theory to practice, enable the players to progress at individual rates, allow them to fail gracefully and give them freedom to explore and discover (Gee, 2003; Squire, 2003). Empirical research by many groups has shown the benefits of video games as learning tools (Clarke & Dede, 2007; Dede, 2009; Klopfer & Squire, 2009; Mitchell, Dede & Dunleavy, 2009).

Different approaches to the integration of games as educational tools for primary, secondary and college level education have been studied. One of the most common is the use of multiplayer online games, which are usually contextualized in virtual spaces called multi-user virtual environments or MUVEs (Clarke & Dede, 2007; Dede, 2009). In this type of game each student plays on his/her computer and interacts virtually through the game with his/her classmates and the teacher (Paraskeva, Mysirlaki & Papagianni, 2010). Another approach utilizes location-based or ubiquitous games. In these, students work collaboratively in an exploratory environment to achieve different goals, assisted by mobile handheld devices that are wirelessly networked and usually enhanced by additional technologies such as GPS and augmented reality (Dede, 2009; Klopfer & Squire, 2009; Mitchell, Dede & Dunleavy, 2009; Liu & Chu, 2010).

Although these two approaches have shown good results in creating engaging learning experiences, they are not well suited to the school classroom, still the most important educational environment in our current system. This is reflected in a number of recent attempts to employ games in the classroom for subject-based learning. Original games have been developed to teach mathematics (Lee & Chen, 2010), biology and genetics (Annetta, Minogue, Holmes & Cheng, 2009), electrostatics (Squire, 2004) and history (Watson, Mong & Harris, 2010), and existing games have been tested for teaching social science topics (Cuenca & Caceres, 2010). What is generally lacking in these experiences is an explicit integration of the game into the pedagogical process of the class. To achieve such integration, several elements need to be assured. Among others, the game should involve all the students in the class, the teacher must have the ability to control the game, and the duration of the game-play sessions should be adjusted to the length of the lecture (Susaeta, Jimenez, Nussbaum, Gajardo, Andreu & Villalta, 2009). In many cases games feel like a replacement for the class instructor rather than a tool to be used and controlled by him/her, potentially prompting some teachers to reject their use (Kebritchi, 2010).

This article presents a framework for the design of educational games and their integration in the classroom that is analyzed through a case study of a game to teach electrostatics. The structure of the article is the following: Section 2 introduces the framework and the different components for designing and integrating the game; Section 3 outlines the game developed within this framework to teach electrostatics; Section 4 describes an experimental application developed to test the game in a real classroom context and sets out the results obtained; and finally, Section 5 presents our conclusions and some suggestions for future research.

2. A framework for the design and integration of classroom games

The design and integration of classroom-based educational games must incorporate both an educational dimension, which defines how to build and integrate the game as a learning tool, and a ludic dimension, which determines how to create an engaging and fun experience (Aleven, Myers, Easterday & Ogan, 2010). The educational dimension addresses two questions that are central to the creation of learning environments: First, what are the learning objectives of the activity? And second, how is the activity integrated pedagogically in the class? (Dillenbourg & Jermann, 2010). The ludic dimension, on the other hand, must tackle the central question in the design of any game: What elements should be included in the game in order to achieve the desired experience? (Schell, 2008). In an educational game the "desired experience" is the fulfillment of the learning goals by the students in the context of the class through an engaging and challenging experience. The ludic dimension of the design process is therefore subject to the educational dimension, meaning the game elements chosen must be constrained by both the learning objectives and the need for pedagogical integration.

Both dimensions are incorporated in our proposed framework for the design and integration of classroom games, shown here schematically in Figure II.1. As can be seen, the educational dimension is divided into two components. The first focuses on establishing the learning objectives of the game, defining the specific learning objectives it must achieve, while the second aims at determining how the game is pedagogically integrated in the class, specifying the pedagogical model to be used and the technology to support it. As for the ludic dimension, it identifies the specific elements the game should have to achieve the desired experience. These elements must incorporate the constraints implied by the educational dimension components.

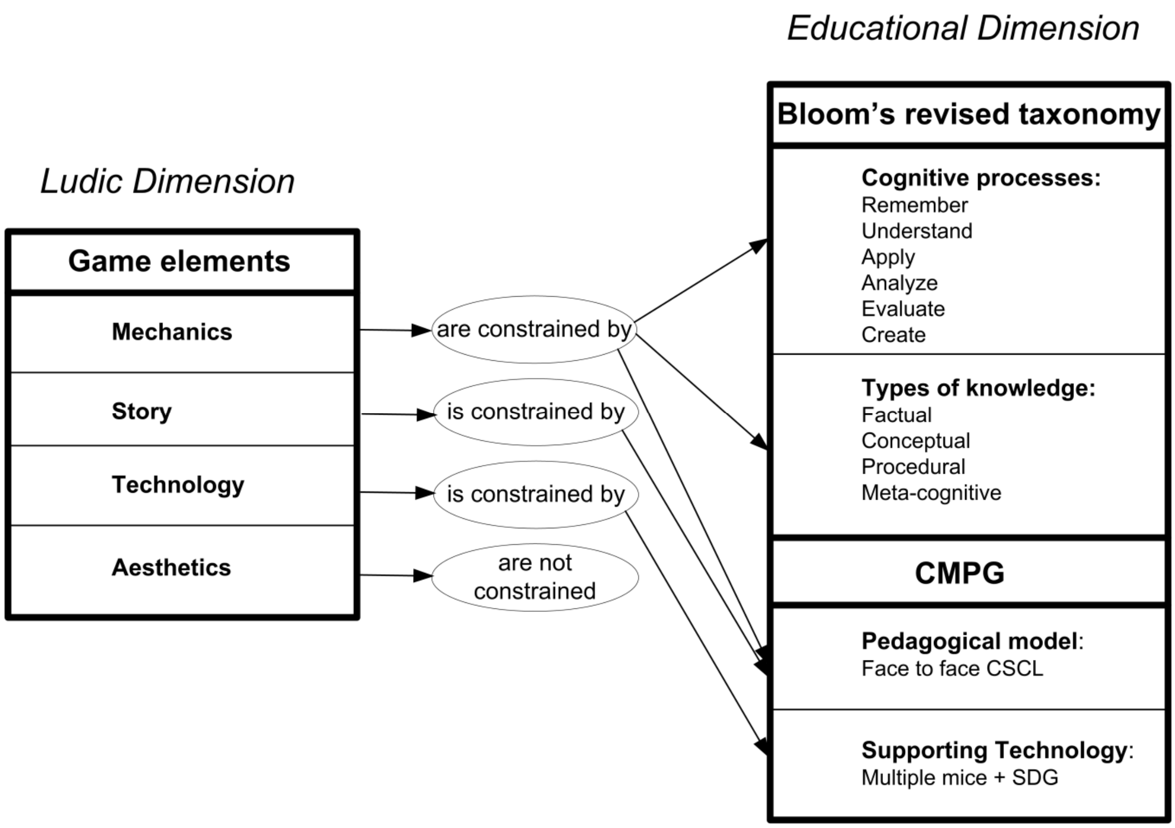

Figure II.1. The two dimensions of the proposed classroom games design framework. The educational dimension defines the pedagogical structure of the game, constraining the elements of the ludic dimension.

2.1 Ludic dimension: game elements

To identify game elements that will reflect the desired educational experience we must first define the main elements in the design of any game. One way of categorizing game elements is the “elemental game tetrad” defined by Schell (2008), which divides all elements into four categories: mechanics, story, aesthetics and technology.

The mechanics of a game describes its procedures and rules, defining how players can achieve the game’s goal. They are the key elements differentiating games from other kinds of media in that they give the former their interactivity (Schell, 2008).

The story describes the sequence of events that unfolds during a game. It can be very simple and linear, or highly complex and branching. The level of storytelling will vary, ranging from games that are completely abstract with very low narrative elements to story-driven games that more closely resemble interactive movies (Schell, 2008).

The aesthetics, as defined by Schell (2008), describe how the game looks (graphic design, colors) and sounds (music, sound effects). They define its general tone, which will affect the feelings a player experiences when playing (Schell, 2008).

Finally, the technology defines the materials and interactions that make playing the game possible, and includes such elements as input devices and displays. It enables the game to do certain things while banning it from doing certain others (Schell, 2008).

2.2 Educational dimension

2.2.1 Learning objectives

The specific learning objectives of an educational activity represent the expected goals the students must have achieved once the activity is completed. A useful tool for defining and classifying learning objectives is Bloom's revised taxonomy (Anderson, Krathwohl, Airasian, Cruickshank, Mayer & Pintrich, 2001), which categorizes them in two dimensions: knowledge and cognitive process. In the first dimension, the taxonomy defines four types of knowledge: factual, conceptual, procedural and meta-cognitive. In the second dimension, six types of cognitive processes are defined: remember, understand, apply, analyze, evaluate and create. The two dimensions together form a taxonomy of 24 different categories for classifying the learning objectives of a specific educational activity.

The game element directly affected by the learning objectives is the mechanics (Aleven et al., 2010). By directly mapping these objectives onto the mechanics, the student is forced to fulfill them in order to successfully complete the game. The actual mapping in any particular case will depend on the subject the game aims to teach, but for any given learning objective category in Bloom's revised taxonomy we can define specific characteristics the game mechanics should have.

The cognitive process categories can be associated with specific types of activities and actions that may be included in the game mechanics as follows:

- Remember: repetitive tasks with auxiliary rewards, keeping the student constantly confronted with the knowledge that must be remembered, keeping him/her engaged with the rewards.

- Understand: free exploration of interactions between objects that provide clear feedback, allowing the student to observe how a given process or concept works.

- Apply: direct action over objects with a specific goal, allowing the student to directly apply the specific knowledge.

- Analyze: problem-solving tasks and puzzles that involve integrating and selecting different elements.

- Evaluate: activities that allow the player to modify and correct existing objects, processes or simulations, check how something works and modify it if necessary to improve it.

- Create: activities that enable the player to build new artifacts, design new processes and test them experimentally.

The knowledge categories determine a number of additional characteristics that the game mechanics must include:

- Factual: an explicit fact must appear as content in the game that can be visualized by the player.

- Conceptual: a specific concept must emerge explicitly from interaction with the game, through its mechanics.

- Procedural: the game mechanics must force the player to explore, execute, modify or create the specific procedure associated with this type of knowledge.

- Meta-cognitive: the game mechanics should provide long-term strategic actions based on the meta-cognitive knowledge.

2.2.2 Pedagogical model and supporting technology

To be successful, the classroom integration of a game must be supported by a pedagogical model that accounts for all the challenges of developing a computer-based activity in a classroom context (Dillenbourg & Jermann, 2010). Although there are many pedagogical models for developing classroom activities, our aim here is to apply one that ensures all students in a class are active participants in their learning within a collaborative environment. To support such team work while enabling the teacher to track each student simultaneously, the activity must take place within a single game world. A suitable model would incorporate these conditions and define what interactions between the students are possible and how they are achieved.

Susaeta et al. (2009) have developed a model that fulfills all of these requirements. Their approach is intended to translate the massive multiplayer online game (MMOG) concept into the classroom. Since the number of students in this context is not massive and play takes place within a single room rather than on the Internet, they changed the terms “massive” and “online” to “classroom” and “presential” respectively, resulting in the new designation “classroom multiplayer presential games” (CMPG).

The CMPG model describes a combination of a pedagogical model and its supporting technology. The pedagogical model is based on the computer supported collaborative learning (CSCL) model (Dillenbourg, 1999) in which the computer is used as a tool to mediate collaboration between students and control the steps or script defining an activity (Dillenbourg, 2002). In a CSCL activity a group of students attempts to achieve an educational goal that can only be accomplished by coordinating the work of each individual member.

The CSCL model has been successfully implemented in the classroom (Zurita & Nussbaum, 2004; Nussbaum, Álvarez, McFarlane, Gómez, Claro & Radovic, 2009) and the work of Susaeta et al. (2009) has built upon this work by incorporating collaborative games in the classroom. In a CMPG game students must work in groups to collaboratively achieve a common objective related to the specific content being taught. The various goals of the game can only be accomplished if the players coordinate their participation in the action, which means in turn that that they will need to verbally discuss issues in order to reach agreements and strategize as a group.

The supporting technology of the CMPG model is a one-to-many computing environment. A single computer is shared by all students through a common display, a type of interaction commonly known as single display groupware or SDG (Stewart, Bederson & Druin, 1999). In the case of CMPG, the shared display is generated by projecting the information from the computer onto a wall. Interaction of the students with the game is then enabled by providing each of them with a mouse connected to the same computer. This multiple mice system has already been utilized in educational applications (Moraveji, Kim & Pawar, 2007; Moraveji, Inkpen, Cutrell & Balakrishnan, 2009). With his/her mouse, each student interacts with the in-class projected virtual world while communicating verbally with his/her peers.

The teacher plays a central role in the CMPG model, acting as an omnipotent being in the virtual scenario. Being in control of the only computer, the teacher has full control of the system. For instance, he/she can pause the game whenever necessary to reinforce particular content or encourage discussion. The game then becomes a tool in the hands of the teacher that can be controlled and paced as particular needs and circumstances arise.

Given the above-described characteristics, the CMPG pedagogical model and its supporting technology in effect define a series of constraints on the different elements of the game. The multiple mice and SDG technology of the CMPG model specify both the input technology and the display technology to be used. The CSCL pedagogical model, on the other hand, imposes the following constraints:

- Story. A CSCL activity is defined by a linear script specifying a series of small tasks with specific goals (Dillenbourg, 2002). The story must therefore also be linear and divided into tasks with specific goals, which in the context of a game are called quests.

- Mechanics. A collaborative learning activity must implement collaborative mechanics that force the group to work together to solve a task. Some of the game mechanics have also therefore to be collaborative, and in addition must satisfy the main conditions for achieving collaboration: positive interdependence, a common goal, coordination and communication, awareness and joint rewards (Szewkis, Nussbaum, Denardin, Abalos, Rosen, Caballero et al., 2010).

3. Case study: a game to teach electrostatics

The framework just described was used to design and develop a game called First Colony for teaching final-year secondary school students the basic concepts of electrostatics. We focused specifically on charge interaction and the law of forces between charges (Coulomb's Law). This topic is a difficult one for most students, who even after college level physics courses are often unable to apply Coulomb's law as well as one would expect (Maloney, O'Kuma, Hieggelke & Van Heuvelen, 2001). Previous educational games developed to teach this subject have failed to correct students' misconceptions regarding the interaction between charges (Squire, Barnett, Grant & Higginbotham, 2004).

In the following subsections we detail the design process of the game, relating it to the two dimensions of the framework and its components. The order of the process is the reverse of that employed above in describing the framework, however. We begin with the educational dimension, specifying the game's learning objectives and pedagogical model, and then proceed to the ludic dimension, defining the elements of the game subject to the constraints imposed by the educational components.

3.1 Educational dimension

3.1.1 Learning objectives

As noted earlier, the first component of the educational dimension is the establishment of specific learning objectives. Once the subject of First Colony was decided, the objectives were identified. This was done based on the expected learning outcomes regarding

Coulomb's Law established by the Chilean Ministry of Education (MINEDUC, 1998) for final-year secondary school students. Categorized in Table II.1 according to Bloom's revised taxonomy, the objectives were then used to define the main game mechanics.

Table II.1**.** Learning objectives of the electrostatic CMPG "First Colony," categorized according to Bloom's revised taxonomy.

<table>
<tr><th></th><th>Understand</th><th>Apply</th></tr>
<tr><td rowspan="4">Conceptual</td><td>Compare the concepts of positively, negatively and neutrally charged objects based on their interaction.</td><td rowspan="2">Apply the conceptual knowledge of Coulomb's Law in one dimension in order to predict the magnitude and direction of the force generated between two charges.</td></tr>
<tr><td>Infer the concept of action and reaction in a forceful interaction of two objects.</td></tr>
<tr><td>Understand the concept of the inverse relationship between distance and electric force.</td><td rowspan="2">Apply conceptual knowledge of the principle of linear superposition of forces to predict the magnitude and direction of the net force exerted on a charge in a system with multiple charges.</td></tr>
<tr><td>Understand the concept of the direct relationship between charge intensity and electric force.</td></tr>
</table>

From this set of learning objectives and the game mechanics characteristics associated with the two dimensions of the framework taxonomy, we derived the following basic list of actions the game players should be able to perform:

- Understand, through exploration and interaction, the concepts of:
    - Positive and negative charges
    - The force between two charges

  - Charges of different intensity
  - Charges located at different distances

- Apply the conceptual knowledge of:
  - Coulomb's law in one dimension
  - The principle of linear superposition of forces

3.1.2 Pedagogical model and supporting technology

The second component of the educational dimension involved analyzing how the CMPG model affected the different game elements. As previously stated, the CMPG's supporting technology defines both the input device (mouse) and the display technology (projected screen). Thus, the players' actions were limited by the actions of the mouse: moving it in two dimensions, clicking two buttons (left and right) and moving the wheel.

The CSCL pedagogical model constrained both the structure of the game's story and its mechanics. The game's story must be linear with clear and well-defined quests. Also, since there are several learning objectives, each quest should focus on just one objective so that the activity advances step by step. As for the mechanics, they must reflect the collaborative aspect of CSCL, meaning the students have to play in groups with a common goal.

3.2 Ludic dimension: game elements

The next step was to specify the elements of the First Colony game in such a way that it would ensure a unified and engaging experience for the players while satisfying the constraints imposed by the educational dimension. In what follows we detail the specifications for each game element included, explaining how the corresponding educational dimension constraints were incorporated.

Mechanics

To satisfy the mechanics requirements defined by the learning objectives, it was decided that each player should control a character that can activate an electric charge around him/her, allowing him/her to directly control the character's intensity and polarity. The players can electrically interact with each other and explore the concepts of positive and negative charge, the force between two charges and its relationship to charge intensity and distance. We also included electrically charged objects that offered a second element of interaction so that the players can directly execute the Coulomb's law procedure on an object and receive clear feedback on the process of the object's movement.

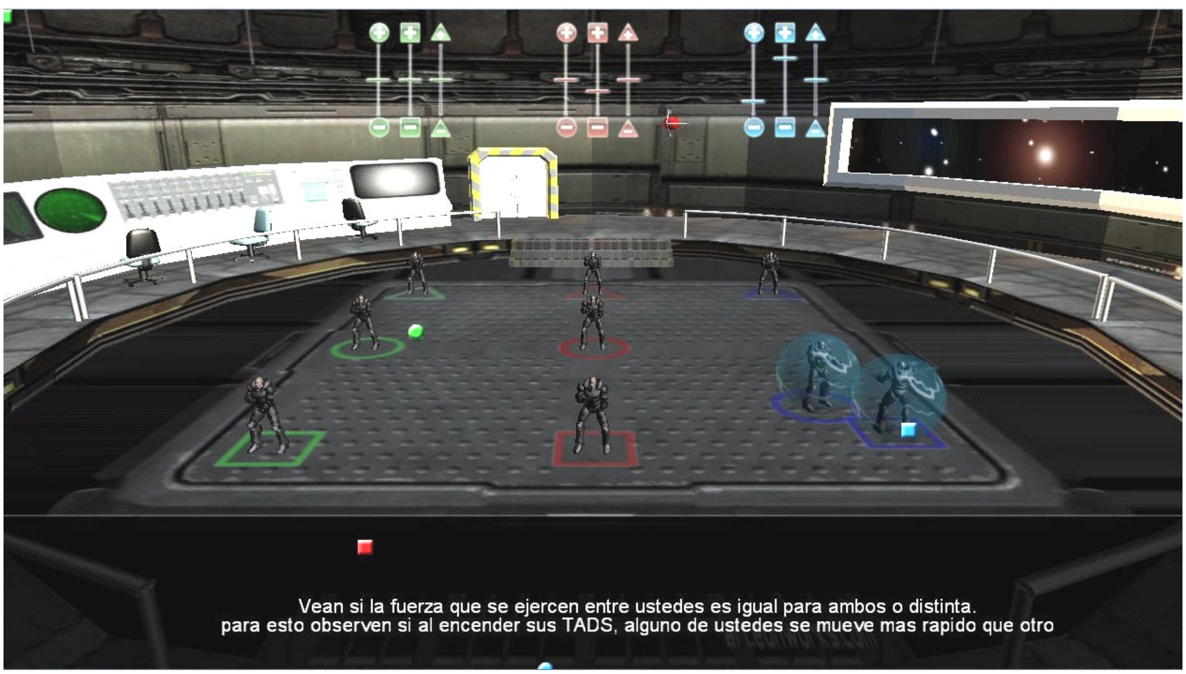

Figure II.2. Each player controls a character that can activate an electric charge around him/her (the spheres in the image), allowing him/her to interact with other players.

Finally, a mechanic was developed to satisfy both the collaborative constraint and the constraint requiring that the players be permitted to execute Coulomb's law in two dimensions.. Three players must work together to move an electric object by applying Coulomb’s law in two dimensions such that the object moves in the desired direction.

Figure II.3. Collaboration was achieved by requiring the players to interact with an object (the crystal in the image) using their electric charges, thus forcing them to coordinate their actions as a group in order to achieve a specific goal.

Technology

Various actions were defined for the mouse, the specified input device. To move a character to a given location the cursor is positioned at that spot and the left button is clicked. The right button activates a player’s electric charge and the mouse wheel defines charge intensity and polarity.

The game world was developed as an immersive 3D environment, taking advantage of the size of the projected screen which can accommodate up to nine students working simultaneously.

Story

Although an electric charge is a real and observable phenomenon, the specific topic of Coulomb's law is hard to contextualize in a real scenario. The game could therefore be set in either a realistic but abstract world of electric particles or in a fantasy-based but concrete world with imaginary electric objects.

Opting for the second approach, we developed a story line for First Colony that incorporates all of the required mechanics described above in a concrete game world. The players assume the role of astronauts from the first human colony on an extra-solar planet. They have been sent on an important mission to bring back a precious crystal found in space. The colony has limited energy resources and the crystal has the unique quality of storing electrical energy. It is fragile, however, so the astronauts can only interact with it at a distance using a special device that creates an electric field surrounding them (to avoid confusion, the concept of field is not actually used in the game).

The structure of the game is implemented as a series of quests grouped into a training phase and a mission phase. The training phase consists of several brief quests that explore a specific learning objective. In each quest a new concept is first introduced by the teacher on a whiteboard or blackboard and then applied in the game (Figure II.4). The students must solve different tasks by controlling their electric charge and working with their classmates. Once this sequence of introductory concepts is completed, the training phase ends.

Figure II.4. In the training quests, the teacher introduces the conceptual knowledge topics to the students. In this scene, the concept of the direct relationship between charge intensity and electric force is being tested by each student.

The mission phase consists of a series of more advanced quests in which the students must collect one or more crystals and push them through a special portal. The first goal of this part of the game is to reinforce the conceptual knowledge covered during the training phase. Thus, when the mission starts the polarity of the players' charges is hidden, forcing them to collaborate with each other and interact with the charged objects to rediscover their polarity (Figure II.3).

The second goal is to have the students apply their conceptual knowledge of Coulomb's law and the principle of linear superposition of forces in one and two dimensions. The one-dimensional version of the law is explored through individual interaction, each astronaut working with a different crystal. In the two-dimensional version, however, the crystals are too big to be moved by a single player, forcing the students to work in small groups of three in order to generate the necessary force to move them (Figure II.4). To succeed in moving a crystal through the portal in the desired direction, the players will necessarily develop a clear understanding of vector addition of forces.

Figure II.5. In the first quest of the mission phase, students must discover their current polarity, which is hidden. This requires them to interact with each other and complete certain information in their respective group's interface, identified by color and displayed on the screen either at the top or in the bottom left or bottom right corner.

Figure II.6. In the mission quests, students must work together to move the crystal, applying their knowledge of Coulomb’s law in two dimensions.

Aesthetics

The visual aesthetics of First Colony were designed to match the storyline, with space environments and astronaut-like characters (Figures II.2- II.6). Sound effects were kept to a minimum and no background music was added so that the students can talk among themselves and the teacher can explain the different concepts without interference.

4. Experimental application

The game as described in the previous section was tested in a real classroom setting to study its impacts on students and analyze its effectiveness as a learning tool. In this section we present the design of this experiment and the results obtained.

4.1 Design of experiment

The experiment was designed for application to a class of final-year students at a public secondary school in Santiago, Chile. It consisted of a one-hour class on electrostatics using our game as the main pedagogical tool. The activity took place under the guidance of one of our researchers who assumed the role of the teacher, pausing game-play whenever the students' performance indicated it was necessary to explain or clarify specific concepts on the blackboard.

In order to assess what the students had learned during the experiment, a pre-test/post-test questionnaire design was adopted. As is usual with this approach (Papastergiou, 2009; Mitnick et al., 2009), the pre-test was administered just before the game was played and the post-test immediately afterwards. It should be noted here that the principal goal of the experiment was to determine the usefulness of the proposed framework as a design aid for the development of classroom games by determining whether the game improved students' knowledge. This experiment was designed as an initial step, centered more on studying the utility of the framework than on comparing the results of the game with traditional methodologies. No control group was therefore used.

The instrument used to measure the expected learning outcomes was a specially designed conceptual evaluation that assessed each outcome (Table 1) by asking specific questions (Appendix A). The evaluation was based on the Conceptual Survey of Electricity (CSE) proposed by Maloney et al. (2001), with certain modifications to ensure all of the desired learning outcomes were covered and any questions on unrelated or more advanced subjects were excluded. The modified version used questions 3 to 10 from the CSE plus 13 additional ones for a total of 21. Before conducting the experiment the test was validated by two final-year physics teachers. A check of the internal consistency of the evaluation, measured by giving the test to 20 students at the school (13 male, 7 female), yielded a Cronbach's alpha of 0.74, above the minimum value of 0.7 required to prove reliability.

An initial pilot study was performed with 9 students (6 male, 3 female) to measure the effect size and estimate a minimum sample size that would yield the desired significance and power levels. The result was a Cohen's *d* value of 1.18, indicating a large effect. From this quantifier we estimated a sample size of 27 to obtain a significance level of 95% and power level of 99% with a one-tailed Student's *t* test.

Based on these values we designed an experiment with 27 students (13 male, 14 female) that was conducted over three sessions. In each session a different group of 9 students played the entire game simultaneously. For the game's collaborative quests, the 9 were randomly assigned to three groups of 3.

To control for the student's previous experience with technology (computers and cell phones) and videogames (computer, console and cell phone games), we developed a brief questionnaire which was answered by each student before the sessions. The results of this survey (Table II.2) showed that most students in the sample, both male and female, were frequent users of computers (only one student used a computer just once or twice a month) and cell phones (only three students did not use cell phones at least once a week). The video game usage questions showed a difference between males and females: only three male students did not play videogames at least once a week on one or more of the platforms, compared to eight female students who played equally infrequently.

Table II.2. The questionnaire controlling for students' previous experience with technology and games showed that most students in the sample frequently used computers and most male students frequently played videogames.

Use of:	*Every day*		*At least once a week*		*At least once a month*		*Less than once a month*		*Never*	
	Male	*Fem.*	*Male*	*Fem.*	*Male*	*Fem.*	*Male*	*Fem.*	*Male*	*Fem.*
Cell Phone	38.4%	71.4%	46.1%	21.4%	0%	7.1 %	15.3%	0%	0%	0%
Computer	76.9%	71.4%	23.1%	21.4%	0%	7.1 %	0%	0%	0%	0%
Videogame	23.1%	7.1%	53.8%	35.7%	7.6 %	7.1 %	15.3%	35.7%	0%	14.2%

To complement the results of the experiment, each session was videotaped with three cameras. Two observers analyzed the recordings after the experiment, making notes every five minutes on important observations related to the students' engagement, the ease of use of the system and any other item of significance.

4.2 Results

The results of the conceptual evaluation pre- and post-tests showed an increase in the average number of correct answers from 6.11 to 10, with standard deviations of 2.24 and 2.74 respectively. To analyze the statistical significance of these results we performed a Student's *t* test for dependant variables, the null hypothesis being that the pre-test and post-test averages were equal and the alternative hypothesis that the post-test average was greater than the pre-test average. To reject the null hypothesis, a one-tailed test was used with a significance level (alpha) of 0.01 (1%). The results of the *t* test rejecting the null hypothesis were statistically significant ($p < 0.00001$), meaning we can conclude with 99% confidence that the average number of correct answers in the evaluation increases after students are exposed to the game.

A post-hoc analysis was also carried out, obtaining a Cohen's *d* quantifier value of 1.58 indicating a large effect size. On the basis of this value, the sample size and the desired significance level (alpha=0.01), we performed a power analysis to obtain the exact power value of the instrument. Thus, it was found that the instrument had a power of 99% (beta=0.01) at a confidence level of 99% (alpha=0.01).

A detailed analysis was conducted on the results of the individual questions and their relationship to the learning objectives. For each student, the results of all the questions associated with each learning objective of Table 1 were averaged, obtaining a single value that measured the student's performance on that objective. A *t* test was performed comparing the pre-test and post-test results for all six learning objective values with a significance level (alpha) of 0.01. For four of the six learning objectives the results were found to be statistically significant ($p < 0.01$); only the objectives "understand the concept of the direct relationship between charge intensity and electric force" and "apply conceptual knowledge of the principle of linear superposition of forces" did not significantly improve.

The possibility of a gender effect was controlled for by dividing the sample and analyzing the male and female groups separately. The results for both revealed improvements, the average number of correct answers increasing from 5.57 to 10.36 for female students and 6.69 to 9.62 for male students. A *t* test showed that in both cases these findings were statistically significant (males: $p = 0.0044$; females: $p = 0.0001$). The difference between the respective improvements of the two gender groups was also tested, but no statistical significance was found ($p = 0.24$).

The effect of previous experience with technology and video game use was also analyzed. To quantify this factor we utilized the Pearson's correlation coefficient, which measures the linear relationship between two random quantitative variables. The test showed no significant correlation between the number of correct answers and previous experience with either technology (cell phone use: $r=-0.3$; computer use: $r=0.12$) or video games (computer games: $r=0.06$; console games: $r=0.16$; cell phone games: $r=-0.03$).

5. Discussion and conclusions

The main contribution of this work is the validation of a proposed framework that can serve as a useful tool for designing video games and integrating them into the classroom. The framework provides a step-by-step design process for defining the elements of a game in accordance with the educational and pedagogical needs as established by the user. The validation itself involved the design and integration of an actual game that was implemented via an experimental application in a real classroom context. The utilization of a CMPG model facilitated the integration process. An evaluation of the experiment demonstrated that in general terms the instructor could successfully use the game as a tool for teaching a particular and relatively complex subject to a group of students.

A number of more specific conclusions can be drawn regarding the game. The statistical analysis of the pre- and post-evaluation results validated its effectiveness for teaching electrostatics, but detailed comparison of the specific learning objective results also revealed its failure to effectively convey either the relationship between charge intensity and force (one of 6 learning objectives for the game) or how to perform vector addition of forces in two dimensions. Regarding the first of these, the failure may have been due to the absence of explicit moments in the game where the students must compare how different charge intensities affect the movement of the charges. As for vector addition of forces, the problem was the lack of explicit visualization of vectors in the game, which made it hard for the students to understand how the forces are summed. We plan to develop a second version of the game that includes explicit quests to explore the difference in force when charge intensity changes and integrates force vector visualizations. We expect it will do better at transmitting the concepts the game reported here proved unable to get across.

An analysis of the test results by student characteristics showed that there was no significant relationship between gender, previous computer use or previous game playing and pre-test/post-test improvement. These outcomes are significant because they contradict the general conception that games are only useful for male students with previous game experience. Additional evidence in the same direction was the excitement displayed by female students while they were playing (one female student even asked where she could download this game). A possible explanation of the game's success among female students is the social component. The collaboration required in some quests adds a social dynamic to the game that traditional challenge-based games lack.
The observations based on the video recordings of the experiment justify three additional conclusions. First, motivation was high during the entire gaming session, demonstrating that the students were engaged by the game and remained so right to the end. Second, the system can be learned rapidly. Indicators such as the number of errors in game actions and interface confusion dropped quickly after a few minutes of game-play, suggesting students were able to learn the game during the training quests and could use that knowledge in later quests. This rapid "learnability" also proves that it is possible to develop games which can be learned and used effectively in a single session. An as yet unanswered question, however, is how much training time teachers will need to master the tool and be able to provide adequate pedagogical support. Third, and finally, although various groups played the game independently, significant positive interaction took place between them.

The generally satisfactory results of the experiment suggest that although the concepts learned were contextualized in a fantasy-based game environment, students can transfer that knowledge to the task of answering questions on standard written tests. The possibility they would not be able to make such a transfer was one of our main concerns while developing the game, but the results furnish solid evidence to the contrary. We believe successful transfer was possible mainly because the guidance and explanation given by the teacher acted as a link between the fantasy world of the game and the real world of the test. Thus, if games are to be used as an educational tool, the teacher's knowledge of both the tool and the concepts is essential. In future work we intend to analyze this factor further.

Several other lines of research are suggested by the experiment reported here. First, considering the success of the framework and the game we have presented, a natural next step would be to compare the game's results with those of traditional classes and develop other games using the same process. A second area for exploration would be to use the same framework for developing more games but with a different pedagogical model and supporting technology. This would isolate the effects of the framework from the pedagogical model. Finally, other elements of the framework could be analyzed such as how differences in the story or the aesthetics of the game might affect the learning outcomes of different students.

III. EXPLORING DIFFERENT TECHNOLOGICAL PLATFORMS FOR SUPPORTING CO-LOCATED COLLABORATIVE GAMES IN THE CLASSROOM

Abstract. Computer Supported Collaborative Learning is a pedagogical approach that can be used to deploy educational games in the classroom. However, there is no clear understanding as to which technological platforms are better suited for deploying co-located collaborative games, nor the general affordances that are required. In this work we explore two different technological platforms for developing collaborative games in the classroom: one based on augmented reality technology and the other based on multiple mice technology. In both cases, the same game was introduced to teach electrostatics and the results were compared experimentally using a real class. The results of our experimental work showed that students significantly increased their conceptual understanding of electrostatics with both platforms. However, there were also some important differences between platforms. While in the multiple mice platform there were no gender differences, in the augmented reality platform boys significantly outperformed girls. In addition, the augmented reality platform was considerably more costly to deploy in a real world setting than the multiple mice platform. These results suggest that it is crucial to carefully consider which technology to use when designing co-located collaborative games, as the technology can have long-term effects beyond those of the games themselves.

1. Introduction

In recent years, many technological devices and systems have been deployed in schools and classrooms with the goal of improving the quality of education. Interactive whiteboards and projectors for every class, netbooks for every child, latest generation computer labs for every school, among others, are being delivered and installed all around the world, in the hope that the availability of this vast amount of technology will somehow improve current educational practices (Kraemer, Dedrick & Sharma, 2009).

However, the reality is different: the mere deployment of this technology has no added educational value in and of itself, and can even be detrimental (Cuban, Kirkpatrock & Perk, 2001). Several studies have shown that without a pedagogical structure associated with the deployment of this technology, the technology has no impact on student learning (Santiago, Severin, Cristia, Ibarrarán, Thompson & Cueto, 2010). The good news is that studies have also shown that when the technology is used as a tool for developing activities supported by a pedagogical model, there can be significant improvement in student learning (Roschelle, Rafanan, Bhanot, Estrella, Penuel & Nussbaum, 2010).

Computer Supported Collaborative Learning (CSCL) is a pedagogical approach that has been successfully integrated into classroom activities using available technology (Zurita & Nussbaum, 2004). In a collaborative learning activity, students work as a group in a coordinated effort to achieve a specific educational goal (Dillenbourg, 1999). There have been several different approaches to deploying this type of activity in the classroom: using one handheld device per child (Zurita & Nussbaum, 2004); using one netbook per child (Nussbaum, Gomez, Mena, Imbarack, Torres, Singer, & Mora, 2010); using one computer for every three children (Infante, Weitz, Reyes, Nussbaum, Gómez, & Radovic, 2010) and even using one computer for the whole classroom (Szewkis, Nussbaum, Denardin, Abalos, Rosen, Caballero, Tagle & Alcoholado, 2010).

Parallel to this growing interest in using technology in the classroom, another simultaneous movement has been pushing for the use of videogames as a learning tool. This movement states that videogames are, in essence, learning environments, and that many of their characteristics can be applied for educational purposes. They allow the players to progress at their own rate, give immediate feedback to actions, allow the transfer of concepts from theory to practice, provide graceful failure, and give freedom of exploration and discovery (Gee, 2003; Squire, 2003). Empirical research by many groups has validated these claims, showing the benefits of games as learning tools (Clarke & Dede, 2007; Dede, 2009; Klopfer & Squire, 2008).

What is generally lacking in previous experiences of using videogames in the classroom is an explicit integration of the game into the pedagogical process of the class. In many cases, games feel like a replacement for the class instructor, rather than a tool for them to use and control. This can prompt some teachers to reject their use (Kebritchi, 2010). To achieve a successful integration, several elements need to be present. Among others, the game should involve all the students in the class, the teacher must have the ability to control the game, and the duration of the game-play sessions should be adjusted to the length of the class (Susaeta, Jimenez, Nussbaum, Gajardo, Andreu & Villalta, 2009).

In this article, we explore the design of technological platforms that support the deployment of co-located collaborative games, taking into account the pedagogical requirements. In order to achieve this we first propose a series of requirements that should be considered when designing these platforms, before applying them to the development of two platforms (Section 2). Using both platforms, and so as to understand the advantages and disadvantages of each, we implement a game to teach electrostatics (Section 3) and perform an experimental analysis with 45 11^{th}graders from a public school in Santiago, Chile (Section 4). Based on the experimental results, we provide a series of lessons learned from the experience that should be taken into account when using these platforms (Section 5).

2. Technological platforms for co-located collaborative games

2.1 Requirements

Several conditions are required to achieve successful collaborative learning among peers: the existence of a common goal, positive interdependence between peers, coordination and communication between peers, individual accountability, awareness of peers' work, and joint rewards (Szewkis, Nussbaum, Denardin, et al, 2010). However, only three of these conditions are significantly affected by the choice of technological platform. The first condition affected is the coordination and communication between peers, given that some technologies are better suited to face-to-face communication than others. The second is individual accountability, given that some input devices cannot be differentiated by the system in certain technologies (e.g. multi-touch tables). The final condition is awareness of peers' work, given that in some platforms all the system information is shared (e.g. single display groupware), while in others it is not (e.g. individual mobile devices).

In addition to the necessary requirements for achieving collaborative learning among peers, the successful orchestration of these activities in the classroom requires additional conditions regarding the role of the teacher (Dillenbourg, 2010). In particular, the teacher should be aware of the activity status of the students, and should also have control of the flow of the activity during the class (Dillenbourg, 2010). The fulfillment of these teacher-centered conditions will also depend on the technological platform. To allow the teacher to be aware of the students' work, there must be some mechanism in the platform that provides real-time feedback to the teacher. To allow teacher control, there must be some mechanism in the platform that allows direct teacher intervention in the students' actions.

Based on these previous conditions, we propose a list of requirements that should be considered when designing technological platforms for supporting co-located collaborative games in the classroom:

- Facilitate teacher awareness and control of the game: The first essential requirement is that the design of the platform must consider how it will help the teacher in mediating between the game and the students. As previous experiences with classroom games have shown, it is essential that the teacher play a participatory role (Habgood & Ainsworth, in press; Squire, Barnett, Grant & Higginbotham, 2004), and the platform should explicitly allow for this participation. The teacher must be included in the information loop of the game, allowing them to control the game flow and also receive real-time feedback about the current status of the students.

- Facilitate awareness of peer's work among students: Most educational videogames require the explicit representation of the virtual objects and elements of the game world. The ability to interact with the system and modify these representations is essential so as to take advantage of the feedback loops that the game provides (Gredler, 2004). It is important, then, that the main game elements that are related to the concepts being taught by the game are visible to every player, and that this visualization is consistent among them in order to achieve peer awareness.

- Allow individual accountability: Individual accountability is one of the essential elements that must be considered in a CSCL activity (Szwekis, Nussbaum, Denardin et al, 2010). In order to achieve this, the system must know which student does which action. Some input technologies such as multi-touch tables or laser pointers do not allow the system to identify each player and thus should not be used in developing this type of platform.

- Allow face-to-face communication and coordination between small groups: Face-to-face interaction is essential for achieving good results in a co-located collaboration environment and must be included in these platforms (Zuirta & Nussbaum, 2004). In addition, the technology should prefer interaction between small groups because evidence has shown that groups of three students are better for this type of collaboration (Zuirta & Nussbaum, 2004).

According to the characteristics previously described, we designed two platforms using different technologies. The first platform used multiple mice connected to a computer, while the second used augmented reality. The following sections describe each platform and detail how each one of the previous characteristics is considered.

2.2 Multiple mice platform

The multiple mice platform is designed around the central idea of taking advantage of multiple input possibilities provided by regular computers, especially the ability to connect and use multiple mice, something which has already been tried in several classroom-based educational activities (Moraveji, Inkpen, Cutrell & Balakrishnan, 2009; Susaeta, Jimenez, Nussbaum et al, 2009). In this platform, students play in groups of three using one computer, with each student controlling one mouse. Each group works with their computer which runs the game logic and graphics independently. The computers are also wirelessly connected to the teacher's computer in order to provide real-time feedback about the students' gameplay and allow the teacher to control the flow of the game, pausing all of the games if necessary. The real-time results of each group are also projected on a screen which allows the teacher to visualize the current state of the game from any place in the classroom. This gives the teacher the flexibility to move around the groups and be aware of all the groups' statuses (Figure II.1).

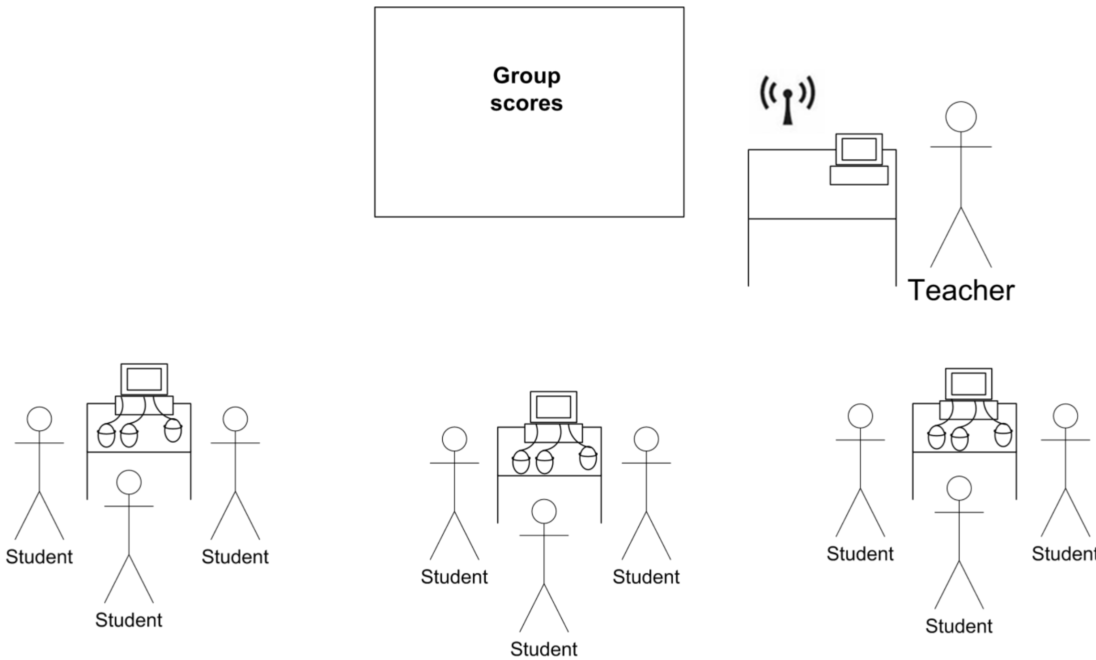

Figure III.1. In the multiple mice platform, groups of three students play on one computer, with each student using a mouse. The computers are networked to a central server that provides real-time information to the teacher as well as projected for all the groups to see.

This proposed platform complies with all of the required characteristics previously discussed:

- Facilitate teacher awareness and control of the game: Teacher involvement is explicitly designed in the platform. Each computer is connected to the teacher's device, allowing them to control the game flow, and receive real-time feedback. This is enhanced by projecting the results onto a screen which allows the teacher to move around the classroom and still visualize the statuses of the different groups.

- Facilitate awareness of peers' work among students: By providing one laptop with a common display for each group, every student in the group can visualize the complete representation of the game world and objects. Because the screen is the only information source for the students, the information is shared between the members of the group, thus making each student accountable for their own work.

- Allow individual accountability: Each student controls one mouse, which serves as their individual input device. Each input device has a symbol associated as a cursor, allowing the student to identify their own device. However, student interaction is limited to the mouse's three degrees of freedom of movement (left-right, up-down, and mouse wheel), and its three buttons (left, middle, right). The system is able to fully identify the actions of each student, assuming that they remain in control of their mouse.

- Allow face-to-face communication and coordination between small groups: Considering that students are facing the screen most of the time, the platform is not ideal for eye-to-eye interaction. However, by being co-located around one computer, the platform does allow for better face-to-face communication between students than a one computer per student set-up.

2.3 Augmented reality platform

The augmented reality platform uses augmented reality technology (Milgram, Takemura, Utsumi & Kishino, 1994) to create a virtual world inside the classroom. This virtual world can be visualized and explored by each student using a tablet. The interaction with the virtual world is achieved by transforming the classroom into the game world. Each desk is covered with a set of fiduciary papers (Figure III.2a), which act as markers, allowing the augmented reality system to place virtual objects over the desks (Figure III.2b). With the use of the device's camera, the system can detect the relative position of each player to the paper marker, thereby identifying the location of each player in the game world (Figure III.2c). To interact with a virtual object, each player must first identify the object by looking through their display. Then, using a series of interface buttons, they can perform the different possible actions.

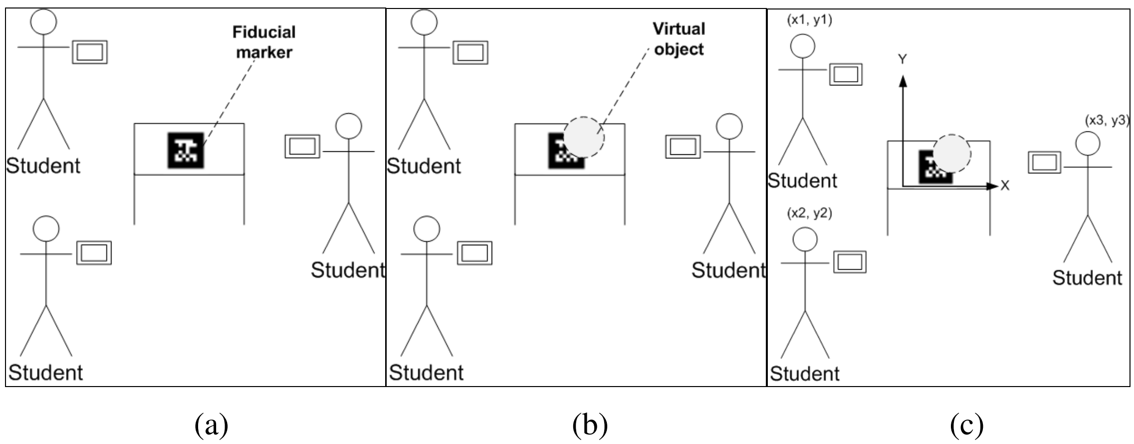

Figure III.2. In the augmented reality platform, paper fiduciary markers are placed on each desk (a), allowing the devices to identify the desk's position and add virtual objects to it (b). The markers also provide a frame of reference that allows the players to be located in the virtual world (c).

Each group of three students works around one desk, which has a specific fiduciary marker. The teacher's computer acts a central server that runs the game logic for every group. Each tablet acts as a client device receiving instruction from the server to update the graphics, and sending the user input back to the server. The teacher's computer is also used to provide real-time feedback about the student's gameplay, and allows the teacher to control the flow of the game, pausing all of the games if necessary. The real-time results of each group are projected on a screen which allows the teacher to visualize the current state of the game from any spot in the classroom. This gives the teacher the flexibility to move around the groups and still be aware of each group's status (Figure III.3).

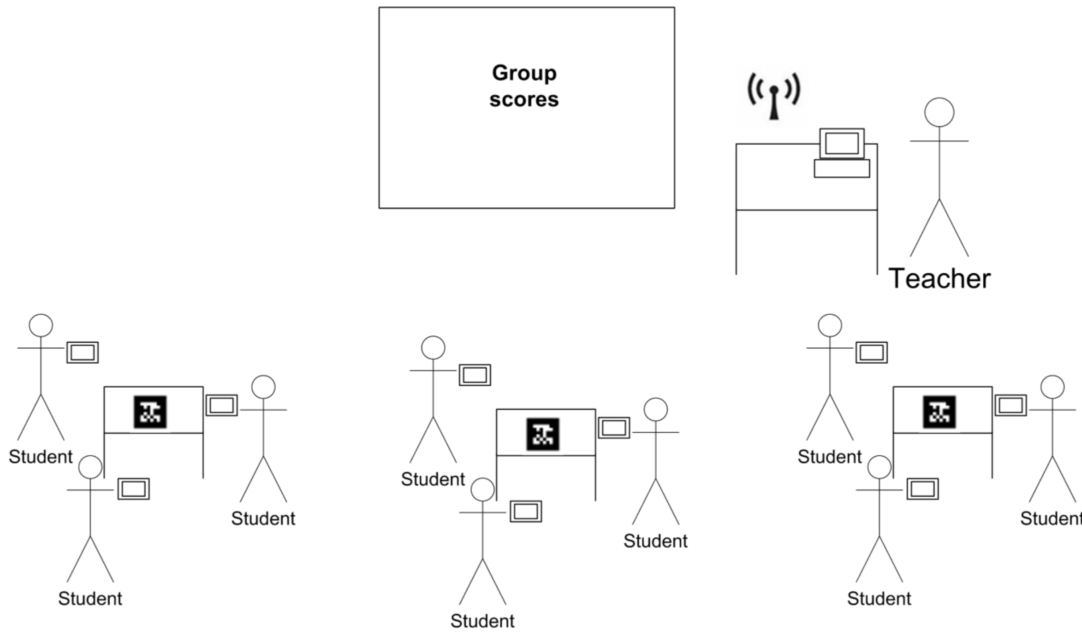

Figure III.3. In the augmented reality platform, groups of three students play around one fiduciary marker using a tablet. The computers are networked to a central server that runs every game and provides real-time information to the teacher, and all the groups via projection.

This proposed platform complies with all of the required characteristics previously discussed:

- Facilitate teacher awareness and control of the game: As with the multiple mice platform, the teacher involvement is explicitly designed in the platform. Each computer is connected to the teacher's device, allowing them to control the game flow and receive real-time information. In addition, by projecting the results onto a screen, the teacher is able to move around the classroom and still visualize the status of the different groups.

- Facilitate awareness of peers' work among students: Through coordination by the central server, every player is shown the same augmented objects, thus achieving shared representation. One difference between the multiple mice platform and the augmented reality platform is that in addition to the shared world, with augmented reality each player can have individual private information shown on each of their screens. However, this has to be managed accordingly, by taking into consideration accountability and various aspects of peer work.

- Allow individual accountability: Each student controls one tablet which serves as their individual input device. Compared to a mouse, the touch screen and keyboard in the tablet allow for a richer possibility of interaction

- Allow face-to-face communication and coordination between small groups: The platform facilitates face-to-face interaction by allowing students to always be facing each other. Small groups are also required to provide enough space for students to move freely around the desks.

3. First Colony: A game to teach electrostatics

3.1 Game description

To test the results of integrating a game in a classroom with both platforms, we used a previously developed game called "First Colony", which was designed with the goal of teaching electrostatics to 11^{th} and 12^{th} graders (Echeverria, Garcia-Campo, Nussbaum, Gil, Villalta, Améstica & Echeverría, 2011). Electrostatics is an interesting area for instructional games as the nature of the interaction is non-intuitive and invisible. For this reason, it has been used in several research projects that designed games and virtual environments, with successful learning outcomes (Squire, Barnett, Grant et al, 2004; Salzman, Dede & Loftin, 1999).

The scope of our game was more limited than in previous games: we focused only on point charges and static electricity forces, which studies have shown to be difficult topics to grasp conceptually (Maloney, O'Kuma, Hieggelke & Van Heuvelen, 2001). The specific learning objectives of the game were:

1. To understand the interaction between objects with positive, negative and neutral charges.
2. To understand the relationship between charge intensity and electrical force.
3. To understand the relationship between the distance separating charges and electrical force.
4. To apply Coulomb’s Law in order to predict the magnitude and direction of the force generated between two charges.
5. To apply the principle of linear superposition to predict the magnitude and direction of the net force exerted on a charge in a system with multiple charges.

In the game, players assume the role of astronauts from the first human colony on an extra-solar planet. They have been sent on an important mission to bring back a precious crystal found in space. The colony has limited energy resources and the crystal has the unique quality of storing electrical energy. However, the crystal is so fragile the astronauts can only interact with it from a distance, and by using electrical force.

Each player controls an astronaut that can activate an electric charge around them (simulating a point charge). The player can also select the charge intensity and polarity and move the astronaut through the game world, modeling the relevant variables required to understand Coulomb’s law (charge and distance). The player then needs to interact with the crystals, which are also electrically charged and, depending on the values selected, will move in a different direction and with different acceleration. The challenge for the player is to move their crystal to a specific location in the game world while avoiding asteroids that would destroy them on contact.

The game's collaborative mechanic is used to teach the principle of linear superposition: some crystals have to be moved by the three players, each applying an individual electric force. With this mechanic, players are not only required to understand Coulomb's law, but also how their individual force adds to the total force, according to the principle of linear superposition of forces.

3.2 Multiple mice version

In the version of the game implemented for the multiple mice platform, each student controls an avatar that represents their astronaut. Each avatar is identified by the cursor symbol associated to each student. The students can move their avatar by locating their cursor in a specific location of the game world and clicking the left mouse button. They can also change their avatar's charge value and polarity with the mouse wheel, and visualize their current charge in the display section of the screen. To activate/deactivate their charge, players have to press the mouse wheel, which will trigger the interaction with the crystal according to the selected parameters (Figure III.4).

Figure III.4. Game implemented in the multiple mice platform: each student controls their astronaut with a mouse. They have to collaborate with their electric charges to produce the electric force that will move the crystal to the portal.

3.3 Augmented reality version

In the version of the game implemented using the augmented reality platform, each student is represented by an astronaut. By moving closer to or farther away from the fiduciary marker, the player changes the astronaut's position in the game world. To change their charge value and polarity, the display of each tablet is augmented with a HUD (Head-Up Display) that allows the player using the touch screen to select their charge and also provides a button for activating/deactivating the charge (Figure III.5).

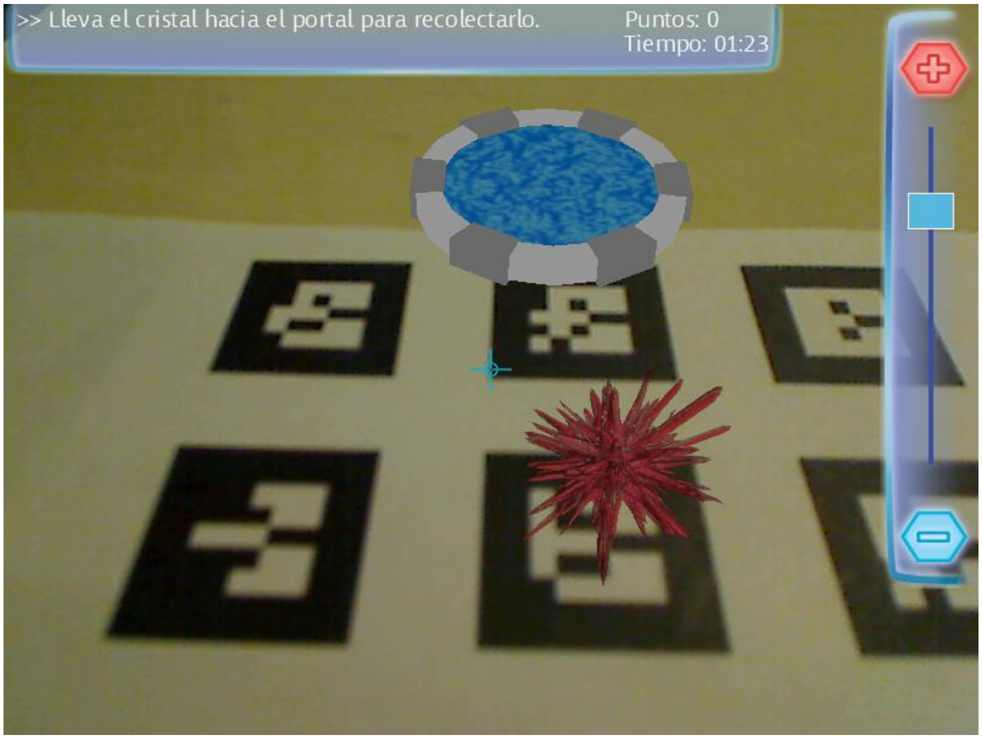

Figure III.5. Game implemented using the augmented reality platform: each player visualizes the augmented world through their visual display and has to move the crystal to the portal by applying electric force using their personal device.

We used Intel's tablet classmate PCs (Intel, 2010) as the mobile platform for the students to play the game. The devices are low cost tablets, specially developed for classroom use, with a 1 GHz processor and 1GB of RAM. The tablets have a flippable webcam at the top of the screen which was ideal for the requirements of our platform. The devices also have a touch-screen which allows the students to perform the actions in the game. using a stylus or their finger.

4. Experiment

4.1 Research questions and Hypotheses

We designed an experiment in order to answer the two research questions of this study: (1) Is it possible to design educationally effective physics games using these platforms? (2) Do student learning outcomes differ when using different platforms?

Our previous experiments had shown that the first version of the electrostatic game was educationally effective, increasing significantly the post-test scores compared to the pre-test scores (Echeverria et al, 2011). Based on these results, our first hypothesis (H1) for this experiment was that the new version of the game implemented in both the multiple mice platform and augmented reality platform would also be educationally effective.

Regarding the augmented reality platform, one of the original design motivations for developing the platform was the concept of immersion, which has been singled out as a key element in helping the learner. A basic definition of immersion is the subjective impression of being involved in a comprehensive and realistic experience that does not take place in the real world (Stanney, 2002; Lessiter et al 2001). There are three main components that help build an immersive experience: the sensorial component, the challenge component, and the imaginative or narrative component (Dede, 2009; Ermi & Mäyrä, 2005). Sensorial immersion refers to physical cues that can be used to trick our senses into believing that what we are experiencing is real (Ermi & Mäyrä, 2005). Challenge- based immersion is closely related to the concept of flow (Csikszentmihalyi, 1990), where the cognitive task being performed puts the player in a state of optimal experience. Finally, imaginative or narrative immersion represents the feeling of being captured in a fantasy world, where the environment, characters, and story are so powerful that they feel real (Dede, 2009).

According to several studies, immersion can improve learning through two mechanisms: first, by allowing the learner to experience multiple perspectives, and second, by situating the learner in a concrete environment (situated learning). Multiple perspectives allow the learner to understand complex systems by exploring different physical points of view, like first person or third person. Also, by taking the role of different characters in the game, the player can experience different psychological points of view (Salzman et al, 1999). Situated learning helps the player contextualize the experience in a concrete environment (Bransford et al, 2000).Studies show that students using immersive activities are more involved and learn the same or more than those using similar but non-immersive activities (Dede, 2009). Additionally, digital immersion allows the students to gain confidence in their academic skills by projecting their real identity onto a virtual character.

Based on this work, our second hypothesis (H2) postulated that because augmented reality technology is more sensory immersive, games played with this platform should have increased educational effectiveness. Therefore, the students using the augmented reality platform should perform better on the test than the multiple mice students.

Previous research on games designed to improve learning has also highlighted that depending on the characteristics of the game designed, differences between genders may appear in the performance results (Steiner, Kickmeier-Rust & Albert, 2009). In the case of our game, the results of the original version (Echeverria et al, 2011) did not show any gender differences, suggesting that the characteristics of the game were adequate for both genders. Based on these results, our final hypothesis for this experiment (H3) was that there would not be any gender difference in either platform.

4.2 Setup

The experiment was carried out with 45 11th grade students from a public school in Santiago, Chile. The multiple mice platform was tested with 18 students (11 boys, 7 girls), while the augmented reality platform was tested with 27 students (12 boys, 15 girls).

A total of 5 sessions were played: two for the multiple mice platform and three for the augmented reality platform. Each gameplay session lasted one and a half hours, with only 9 students participating at a time. The 9 students who participated together in each session were randomly assigned into three groups of three. Because of this randomization, some groups were gender-mixed, but others were only students of the same gender. All students participating in the experiment belonged to the same class and knew each other.

A pre-post test design was used to compare the learning achieved with the game. The instrument used to measure the expected learning outcomes was a specially designed conceptual evaluation that assessed each outcome by asking specific questions (Appendix A). The evaluation was based on the Conceptual Survey of Electricity (CSE) proposed by Maloney et al. (2001), with certain modifications to ensure that all of the desired learning outcomes were covered and any questions on unrelated or more advanced subjects excluded. The test was previously validated with 20 students, yielding a Cronbach's alpha of 0.74, above the minimum value of 0.7 required to prove reliability.

4.3 Session Description

One of our researchers acted as the teacher for the session, carrying out a previously defined script that was repeated in every session. Each session started with the pre-test being taken by all the students in the session. After that, the teacher gave an introduction to the topic to familiarize students with the general ideas and terminology. This introduction was carried out interactively, asking the students about the basic knowledge on the subject to assess what they already knew. Throughout this introduction some of the students were already with their corresponding groups and devices, however they could not interact yet with the game because it was paused.

After finishing the introduction, the teacher explained the basic idea of the game, how students should interact with their devices, and its relation to the concepts introduced. The teacher then proceeded to send a message through his laptop to unpause the student devices and start the tutorial part of the game. Each tutorial level added a new game element which corresponded to a conceptual element explained by the teacher. The teacher received the results of the student performance in real-time and could pause the game to make specific clarifications. The teacher controlled the flow of the game, advancing to the next tutorial level only when every student had accomplished the minimum requirement. This allowed the teacher to keep the whole class working on the same concepts simultaneously.

After the tutorial phase of the game, the students then played the mission part. This part was collaborative and included different, increasingly difficult levels that encompassed all the relevant instructional concepts, and added additional gameplay challenges. In this part, there was no general explanation provided by the teacher, rather he moved around the room to observe the different groups and answered questions when the students were confused. Similar to the tutorial levels, the students controlled the flow of mission levels, advancing only when all groups had accomplished the minimum goal for the level. The post-test was administered to the students immediately after all the groups finished all the levels.

4.4 Results and Statistical Analysis

The results of the conceptual evaluation pre- and post-tests showed an increase in the average number of correct answers from 4.27 (1.74) to 6.22 (3.13) for students who played the multiple mice version, and an increase in the average number of correct answers from 3.51 (2.04) to 6.37 (2.89) for students who played the augmented reality version. For both cases, to analyze the statistical significance of these results we performed a student's t test for dependant variables. The null hypothesis was that the pre-test and post-test averages were equal and the alternative hypothesis was that the post-test average was greater than the pre-test average. To reject the null hypothesis, a one-tailed test was used with a significance level (alpha) of 0.05 (5%). Because the t test rejected the null hypothesis, the results were statistically significant for both the multiple mice platform ($t(17) = 1.73$, $p < 0.05$) and the augmented reality platform ($t(26) = 1.70$, $p < 0.05$). This translates into a 95% confidence level that the average number of correct answers in the evaluation increases after students are exposed to both versions of the game.

Additionally, a power analysis was performed to measure the effect size of both versions. The analysis of the multiple mice version resulted in a Cohen's d quantifier value of 0.79, indicating a moderate effect size. The analysis of the augmented reality version resulted in a Cohen's d quantifier value of 1.17, indicating a large effect size.

To compare the effects of both platforms, we used an ANCOVA analysis with the students' post-test results from each version, using the pre-test results as co-variable. The detailed results of the ANCOVA are shown in table III.1. The statistical analysis of the test scores for both platforms showed that there were no statistically significant differences between the results obtained by the students who played the multiple mice and those who played the augmented reality versions ($F = 0.78$; $p = 0.38$). However, significant statistical differences were found between boys and girls in the augmented reality group, where boys outperformed girls, and also between boys of the augmented reality group and boys of the multiple mice group, where the former outperformed the latter (Table III.2).

Table III.1. ANCOVA results of the comparison between platforms (k=2)

Source	SS	df	MS	F	P
Adjusted means	5.45	1	5.45	0.78	0.38
Adjusted error	293.03	42	6.97		
Adjusted total	298.49	43			

Table III.2. Test results of comparison between the multiple mice version and augmented reality version

	Gender	Multiple Mice		Augmented Reality	
Test		Mean	Std. Dev.	Mean	Std. Dev.
Pre-test	Boys	4.27	1.67	4.08	1.97
	Girls	4.28	1.97	3.06	2.05
	Total	**4.27**	**1.74**	**3.51**	**2.04**
Post-test	Boys	6.27	3.69	7.75	2.66
	Girls	6.14	2.26	5.26	2.65
	Total	**6.22**	**3.13**	**6.37**	**2.89**
Adjusted Post-test	Boys	6.19	-	7.82	-
	Girls	5.90	-	5.38	-
	Total	**5.87**	**-**	**6.60**	**-**

5. Discussion

Although the sample size of the experiment was small, the experimental results provide initial insights into our research questions and hypotheses. Our first hypothesis (H1) stated that both versions of the game would be educationally effective for students. Students who played both games showed a significant increase in their conceptual knowledge after only one session. This proved both implementations to be educationally effective, thus proving our first hypothesis. These results suggest that the essential aspects of an effective educational game transcend technology.

Our second hypothesis (H2) stated that the students who played the augmented reality version of the game should show significantly higher test scores than the ones who played the multiple mice version, based on the higher sensory immersion of augmented reality technology. The comparison between platforms showed no difference in educational effectiveness, contradicting our second hypothesis and suggesting that sensory immersion may not be an essential element for the specific learning objectives of this game.

Our final hypothesis (H3) stated that because the designed game includes elements targeted at both genders, there would not be any relevant gender differences in test scores and student engagement in the game. The results of the experiment showed that for the augmented reality platform there were statistically significant differences between male and female post-tests, thereby contradicting our third hypothesis. Considering the lack of significant difference in the test scores of boys and girls who played the multiple mice version of the game, it is possible that the platform is creating a gender gap extrinsic to the game.

A possible explanation of these gender differences, consistent with observations performed during the sessions, is that girls had more trouble in learning to use the augmented reality platform. This difficulty hindered their ability to understand the concepts and achieve a positive experience with the game. Some evidence suggests that, on average, girls have fewer 3D spatial skills than boys (Voyer, Voyer & Briden, 1995), which could explain the gender differences seen in our results. For the augmented reality platform, 3D spatial skills are essential. This issue could be resolved by providing a training session before starting the game, however further experimentation is required.

6. Conclusions and Future work

The success of both platforms as tools for increasing students' conceptual understanding provides important validation for the use of these types of systems in the classroom. Conceptual understanding in physics is essential for achieving deep learning (diSessa, 1998; Forbus, 1997; Hewitt, 2002), but engaging students in complex thinking about models and processes is not easy, and traditional methodologies for teaching may not be well-suited for this goal (Bransford, Brand & Cocking, 1999). We believe that games represent a practical alternative for achieving these learning objectives, and through this study we have demonstrated how to integrate these games as practical tools for the teacher.

An important conclusion from this experiment is that the overhead cost and complexity of a specific technological platform is justified only if the educational benefits obtained by its use are significantly greater than a cheaper and simpler alternative. The augmented reality platform represents both a more expensive and complicated option than the multiple mice platform. In terms of costs, the augmented reality platform requires one suitable tablet device per student, compared to the multiple mice platform which requires one laptop for every three children. In terms of complexity, the augmented reality platform requires a more extensive setup: arranging the desks to provide space for student movement, locating the fiduciary markers on each desk, and adjusting the lighting conditions if necessary. There is also the cost of the platform's learnability. As our observations showed, the augmented reality platform was more difficult to learn than the multiple mice platform, especially for girls. Finally, there are also difficulties for the teacher when using this platform. In the multiple mice platform, the teacher could easily visualize the current state of each group by looking at their computer display. On the other hand, in the augmented reality platform, the teacher needed to directly observe the displays of the three students in order to get a complete picture of that group's status. This added step may complicate the teacher's ability to give guidance and generally help the students.

All of the aforementioned implicit and explicit costs of the augmented reality platform suggest that its use is only justified when the benefits are considerably larger than an alternative platform. For this experience, we believe that the benefits obtained were not enough to compensate for the costs, and therefore the multiple mice platform is better suited for presenting the game. The multiple mice platform represents a simple yet effective technology that can be leveraged for deploying games inside the classroom. The platform effectively transforms a class into a fun, entertaining experience by combining collaborative play between students with competitive play among the whole class. Additional games should be designed using this platform in order to provide further validation and discern to what extent the obtained results can be applied to other cases.

Ultimately, this experience suggests that the overall cost of deploying the augmented reality platform outweighs any of its possible benefits. However, we believe that the successful deployment of an augmented reality game in the classroom sets a useful precedent for future work. A true augmented reality platform that integrates real objects could provide experiences that cannot be achieved with a traditional computer, These experiences could then allow for the creation of games that combine virtual simulations with real experiments, facilitating the transfer of knowledge from the game world to the real world.

IV. THE ATOMIC INTRINSIC INTEGRATION APPROACH: A STRUCTURED METHODOLOGY FOR THE DESIGN OF GAMES FOR THE CONCEPTUAL UNDERSTANDING OF PHYSICS

Abstract. Computer simulations combined with games have been successfully used to teach conceptual physics. However, there is no clear methodology for guiding the design of these types of games. To remedy this, we propose a structured methodology for the design of conceptual physics games that explicitly integrates the principles of the intrinsic integration approach for designing instructional games (Habgood & Ainsworth, 2011) with an atomic analysis of the structure of games (Koster, 2005; Cousins, 2005; Cook, 2007). To test this approach, we redesigned an existing game to teach electrostatics and compared the educational effectiveness of the original and redesigned versions. The original version was qualitatively intrinsic, but applying our proposed methodology refined and deepened the intrinsic nature of all core learning goals within the game. Our studies also compared an endogenous fantasy version of the game with a non-fantasy version. Our results showed that students who played the game which had been redesigned using the Atomic Intrinsic Integration Approach achieved a statistically significant improvement in results and showed fewer conceptual problems than the students who played the original version. The fantasy and non-fantasy versions, however, did not display any significant differences in outcomes. Based on the analysis and redesign of the game, we defined one possible methodology to assist in the design of games for the conceptual understanding of physics. We believe that this methodology could be a simple and useful guide for designing other conceptual physics games.

1. Introduction

The conceptual understanding of complex processes and models is essential to the learning of science. In physics in particular, many educators advocate the prioritization of the conceptual and qualitative understanding of basic principles over the use of mathematical formulae (diSessa, 1998; Forbus, 1997; Hewitt, 2002). However, engaging students in complex thinking about models and processes is not easy, and traditional methodologies for teaching may not be well suited to this end (Bransford, Brand & Cocking, 1999).

One methodology that has been used to teach physical phenomena conceptually is through computer simulations - programs that contain a model of a system or process (de Jong & van Joolingen, 1998; Perkins, Adams, Finkelstein, Dubson, LeMaster, Reid et al 2006; Wieman & Perkins, 2006). Computer simulations can be used for science learning by giving the learner the task of inferring the characteristics of the model underlying the simulation (de Jong et al, 1998). One advantage of using simulations is that they can potentially lead to kinds of knowledge that are qualitatively different from the knowledge acquired from more traditional instruction (Swaak & de Jong, 2001).

However when computer simulations are used for discovery learning without any additional instructional support, they show no better results than traditional methods (Gredler, 2004). The reason for these poor results is that learners encounter several problems when only using simulations: they have difficulty finding new hypotheses to test, they design inconclusive experiments, and do not exploit the whole range of possibilities provided by the system (de Jong et al, 1998).

The integration of computer simulations with games has been shown to be one possible solution to these problems (de Jong et al, 1998; White, 1984). Adding specific goals and challenges within the simulation and structuring its progression through game levels has shown marked improvements in the learning outcomes in comparison with non-game simulations (de Jong et al, 1998). Games are useful in this context because they emphasize the process of reflection: unlike a linear process, learning with games follows a cyclical pattern of experience, reflection on that experience, drawing of conclusions based on these reflections, and the formation of a plan for a new action based on those conclusions, before acting once again (Paras & Bizzochi, 2005).

The idea of combining games with simulations has been successfully applied to the design of games for the conceptual understanding of physics. Games for teaching both Newton's laws of motion (White, 1984) and Maxwell's laws of electromagnetism (Squire, Barnett, Grant & Higginbotham, 2004), have been developed and tested with successful results, demonstrating that they improve the learning outcomes when compared with other approaches, such as inquiry-based learning (Squire et al, 2004) and unguided discovery learning (White, 1984).

Although previous research on physics games has validated their use as an effective tool for achieving conceptual understanding, it is not clear how to generalize their results for the design of other physics games. An important research question that remains is how to transform a physics simulation into an educationally effective and engaging game.

In this article we present a structured methodology for the design of such games. To formulate this methodology we started with a pre-existing and tested game for teaching conceptual physics (Section 2.1) and performed an analysis to improve its learning outcomes (Section 2.2). Based on that analysis we redesigned the game, applying our proposed methodology (Section 2.3), and validated it experimentally in a classroom setting (Section 3). Based on this experience we generalized the methodology for it to be applied to other games in the discussion section (Section 4). Finally, we present relevant conclusions regarding this experience (Section 5).

2. Game design and analysis

2.1 Original design and experimental study

The original game which we developed was called "First Colony", and its goal was to teach electrostatics to 12th graders (Echeverria, Garcia-Campo, Nussbaum, Gil, Villalta, Améstica et al, 2011). Electrostatics is an interesting area for instructional games as the nature of the interactions is non intuitive and invisible. For this reason, it has been used in several research projects that designed games and virtual environments for the topic, obtaining successful learning outcomes (Squire et al, 2004; Salzman, Dede & Loftin, 1999).

The scope of our game was more limited than in previous games: we focused only on point charges and static electricity forces, which studies show to be difficult topics to grasp conceptually (Maloney, O'Kuma, Hieggelke & Van Heuvelen, 2001). The basic physical laws that were simulated in the game were Coulomb's Law (Equation IV.1a) and the principle of linear superposition of forces (Equation IV.1b). Coulomb's Law states that the force between two static point charges is proportional to the magnitude of both charges, and inversely proportional to the square of their distance. The principle of linear superposition states that the total force exerted on an object is the vector sum of all the individual forces affecting it.

$$\overrightarrow{F_{12}} = k\,\frac{q_1 q_2}{r^2}\hat{r} \qquad \text{(a)}$$

$$\vec{F}_j = \sum_i \overrightarrow{F_{ij}} \qquad \text{(b)}$$

Equation IV.1. Coulomb's Law (a) and the principle of linear superposition of forces (b).

The specific learning objectives of the game were:

1. To understand the interaction between objects with positive, negative and neutral charges.
2. To understand the relation between charge intensity and electrical force.
3. To understand the relationship between the distance between charges and electrical force.
4. To conceptually apply Coulomb's Law in order to predict the magnitude and direction of the force generated between two charges.

5. To conceptually apply the principle of linear superposition to predict the magnitude and direction of the net force exerted on a charge in a system with multiple charges.

The game was integrated as part of a class, where the teacher first introduced the basic concepts related to electrical force, and then allowed the students to play. The game was played in groups of three students, where each student controlled one mouse and worked collaboratively in groups of three. The teacher had control of the computer that ran the game, and could pause the gameplay when necessary in order to reinforce any concept that was not clear.

In the game, players assume the role of astronauts from the first human colony on an extra-solar planet. They have been sent on an important mission to bring back a precious crystal found in space. The colony has limited energy resources and the crystal has the unique quality of storing electrical energy. The crystal is fragile, however, so the astronauts can only interact with it from a distance using electrical force.

The game was experimentally tested with 27 12th grade students from a public school in Santiago, Chile (Echeverria et al, 2011). A pre-post test experimental design was developed in which the students took a conceptual survey of electrostatics before and after the one hour session. The test scores increased from an average of 6.11 correct answers in the pre test, to 10.00 correct answers in the post test, a statistically significant result with 99% confidence ($p < 0.00001$) and a large effect size (Cohen´s D = 1.58).

Although the general results of the game were positive, a more detailed analysis showed that not all students were learning from the game. The percentage of students that improved after playing the game was only 66.66% in questions related to Coulomb's law, and only 62.07% in the ones that related to the principle of linear superposition. These results implied that more than a third of students were not increasing (or even worse, were decreasing) their conceptual knowledge of both laws after having played the game. This suggested that the methodology used to design the game was incomplete, and that a better design approach was required.

2.2 Game analysis

To understand how best to modify the original game and improve the learning outcomes of the students who played it, we initially performed an analysis of the game to identify its core structure. There are different approaches for analyzing the structure of games (Cousins, 2005; Cook, 2007; Koster, 2005), however one common aspect of most approaches is the description of games as collections of *game atoms*, which are “the activities enacted by a player in a game as mediated by an underlying set of rules, mechanics and affordances” (Koster, 2005). These game atoms, also called *ludemes* (Cousins, 2005) or *skill atoms* (Cook, 2007), represent the building blocks of the game, and combine to create the core gameplay structure. Each game atom represents a feedback loop between the player and the game (Cousins, 2005), involving three elements: an action performed by the player, a simulation or computation performed by the game in response to the action, and feedback provided by the game to the player as a result of the simulation (Figure IV.1).

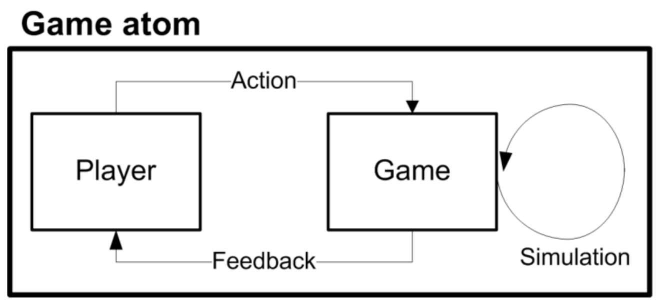

Figure IV.1. A game atom represents a feedback loop in the game, where the player executes an action and the game performs a simulation, and provides feedback to the player.

Game atoms are combined recursively to build the structure of a game: low-level atoms represent the basic actions that the player can perform using the input devices, and by successively combining these, higher level atoms are formed, which represent higher level activities that the player can perform in the game, when the lower level atoms are mastered (Cousins, 2005; Cook, 2007). In the original version of First Colony, the lower-level atoms of the game were the three actions that the player could perform directly with the mouse: move their avatar on the screen, select the value of their charge, and activate the charge to allow its interaction. By combining these three atoms, the player could interact with the crystals, applying an electric force that moved them, with different accelerations depending on the values of each player's charges and their locations. Finally, by moving the crystals, the players were able to achieve the goal of the game by placing them in specific targets located on the screen (Figure IV.2).

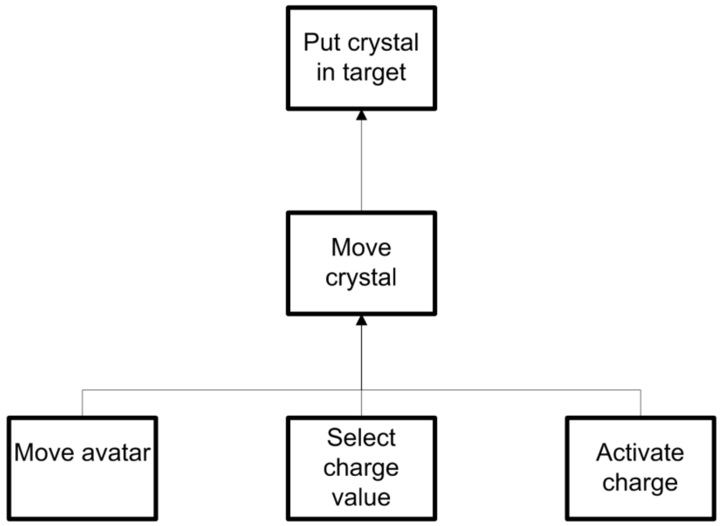

Figure IV.2. Structure of the original version of First Colony

This diagram does not fully describe the game interactions or all the possible sequences of actions to win the game, but it does provide a useful tool for analyzing what the core activities in the game are and how each of the higher level activities depends on mastering the ones at lower levels.

Although the atomic analysis of the game provides a useful way of understanding its core structure, it does not give any guidance on how this structure should be changed to improve the instructional value of the game. One general approach that has been successfully used to design instructional games is "intrinsic integration" (Habgood, 2005). This approach is based around the idea that the learning content should be completely integrated with the core game structure (Habgood & Ainsworth, 2011), defining the subset of activities that the player will undertake most frequently during the game experience, and those that are indispensable to winning the game (Fabricatore, 2007). The intrinsic integration approach identifies two principles that should be included in order to create an educationally effective and engaging game. The first is to incorporate the learning material into the structure of the gaming world and the player's interactions with it and provide an external representation of the learning content that is explored through the core mechanics of the gameplay. The second is to deliver learning material through the parts of the game that are the most fun to play, riding on the back of the flow experience (Csikszentmihalyi, 1990) produced by the game and not interrupting or diminishing its impact (Habgood et al, 2011).

A secondary aspect of the intrinsic integration approach is that the fantasy element of a game cannot be justified in itself as a critical means of improving the educational effectiveness of digital learning games (Habgood, 2005). The intrinsic integration approach suggests that there is a logical hierarchy when designing an intrinsically integrated game. This hierarchy firstly prioritizes the learning content, then the game mechanics and finally the fantasy context (Habgood et al, 2011). Fantasy in instructional games, therefore, is only important in terms of its motivational value, and not because it improves the educational effectiveness of the game. This idea contradicts previous research done on instructional game design (Malone & Lepper, 1987; Rieber, 1996).

2.3 Game redesign

2.3.1 The Atomic Intrinsic Integration Approach

Combining intrinsic integration with an atomic analysis of the game provided us with a structured methodology for redesigning the game. We called this methodology the *Atomic Intrinsic Integration Approach.* The game was redesigned by modifying the original game's atomic structure according to the two guiding principles of the intrinsic integration approach:

(a) *Incorporating the learning material within the structure of the gaming world and the player's interactions with it and provide an external representation of the learning content that is explored through the core mechanics of the gameplay*

In the original version, neither the electrical force between two charges nor the total forces on one charge were directly represented by game atoms. The effect of the forces was only indirectly represented by the movement of the crystal, and because the movement of the crystal was affected by all the players, the effect of the force generated between one player and the crystal could only be seen when no one else was interacting.

To resolve this representation problem, we overlaid arrows on the test charge that directly represented the direction and magnitude of the force being applied between players and the test charge, based on Coulomb's Law. To differentiate the force applied by each player, next to each arrow we also showed the player's symbol (a square, circle or triangle). We added an extra arrow with a different color, which represented the added force generated by all players, applying the principle of superposition (Figure IV.3).

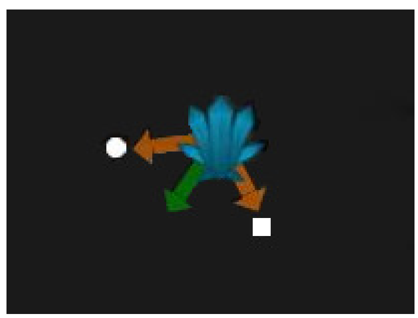

Figure IV.3. Arrows were shown next to the crystal to provide an external representation of individual forces and the total force.

With this modification we achieved two goals. Firstly, the effect of Coulomb's Law and the principle of superposition were integrated as separate game atoms, which provided specific feedback through their corresponding arrows. Secondly, by separating the representation of forces from the movement itself, the game allowed the players to conceptually separate the concept of force, which was essential to the learning objectives of the game, from the movement of the test charges, which was merely an indirect representation of the forces.

However, in the initial testing sessions in which the game was played including these modifications, a problematic side effect appeared. Because the players were provided with direct feedback about the forces, they could achieve the goal of moving the crystal to the target by trial and error, never needing to reflect on how to generate a specific force, which defeated the main purpose of the game. To solve this issue, we decided to progressively remove the arrows as the player advanced in the game, completely hiding them in the final levels. In this way, the arrows acted as scaffolding for the first part of the game, and then, when removed, the players were forced to apply their acquired knowledge to finish the game.

(b) Delivering learning material through the parts of the game that are the most fun to play, riding on the back of the flow experience produced by the game and not interrupting or diminishing its impact.

Observations made during the gameplay sessions of the original version of the game showed that, although players enjoyed the game at the beginning, they lost interest in the game as the session progressed, which suggested a clear problem in the flow experience. In addition to this engagement issue, there was also an educational problem with the challenge structure of the game: there was no losing condition in the game and many students could win the game by mere trial and error, without having to reflect on the underlying concepts.

To solve both of these problems, we decided to create additional challenges by adding static and moving obstacles to the world (Figure IV.4). If the crystal collided with an obstacle they were destroyed, and the level started over, which forced the players to reflect on the physical concepts before trying to move the crystals. The addition of obstacles also provided more variety in the levels of the game, with the aim of positively impacting the flow experience.

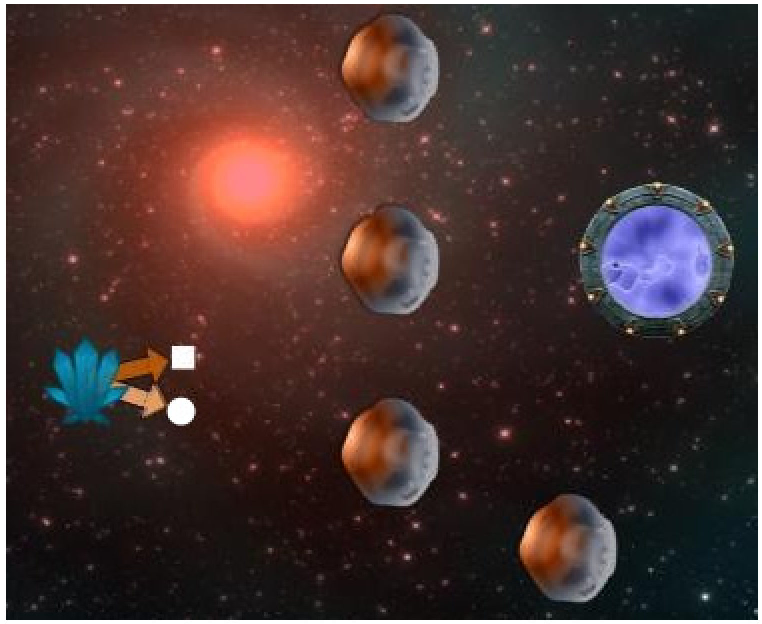

Figure IV.4. Static and moving obstacles were added to increase the flow experience and force player reflection on the concepts.

The redesigned structure of the game is shown in figure IV.5. Two game atoms were added in order to explicitly represent the forces through arrows ("generate electrical force", "generate total force"), and two additional game atoms were added to increase the challenge and force reflective strategies among players ("avoid static obstacles", "avoid moving obstacles").

The game atoms were introduced progressively into the game, starting with the basic atoms in the tutorial, and eventually adding the obstacle atoms to the mission levels. Also, as explained before, the force arrows were gradually removed from the game, in order to force a deeper reflection on the concepts.

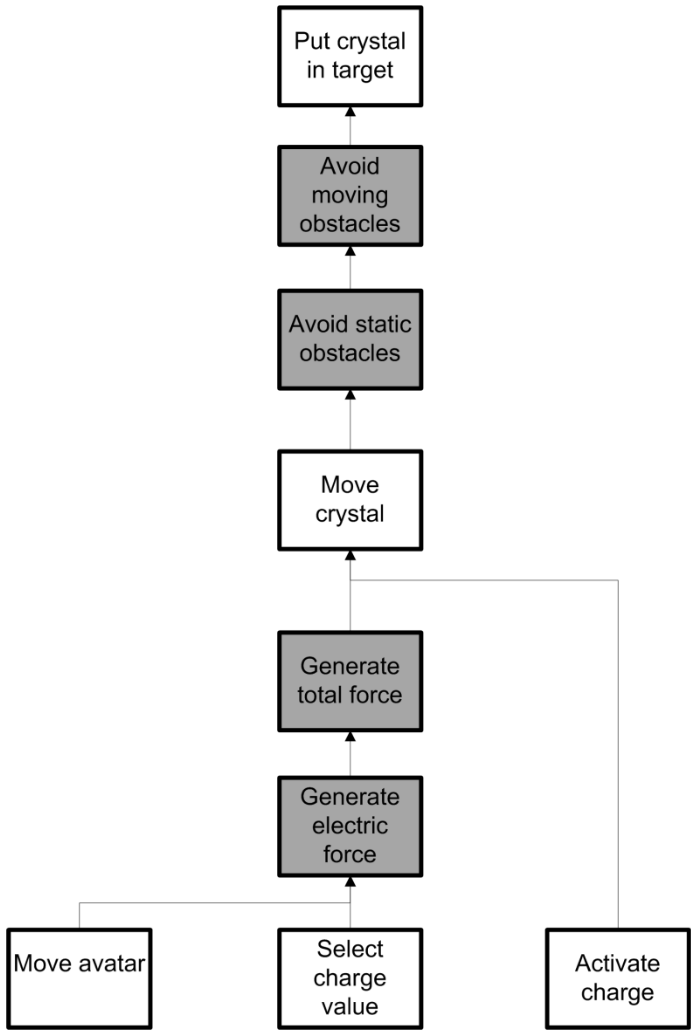

Figure IV.5. Structure of the redesigned version of First Colony. Colored blocks represent new game atoms added to fulfill the intrinsic integration principles.

2.3.2 Fantasy and non-fantasy versions of the game

To analyze how the fantasy context of the game affected the educational effectiveness and engagement of players in the game, we modified the game applying the endogenous fantasy approach for increasing the intrinsic motivation of instructional games (Malone et al, 1987), which is based on two principles: (a) the skill being learned and the fantasy depend upon each other; (b) there is an integral and continuous relationship between the fantasy context and the instructional content being presented.

Our analysis of the original version of the game suggested that these two principles were already being satisfied: the story was centered on electrically charged crystals, and applying the physical laws to move these crystals was essential to fulfill the challenge presented by the story. However, we believed the fantasy aspect of the game, and especially how the narrative was presented, could be improved in order to enhance the endogenous fantasy. In order to improve the story, we applied Dickey's principles for game design narratives (Dickey, 2006) to analyze the game, and found that the only principle that was not considered was to "*develop cut scenes to support the development of the narrative story line*". We added four cut scenes to the game. At the beginning, the first cut scene presented the backstory of the game as well as the environment and setting, and the initial challenge of collecting crystals to save the colony. A second cut scene appeared at the end of the training levels, marking the end of the first part of the game and the beginning of the actual mission. A third cut scene was shown before the last level, where a climatic challenge was added - an asteroid field was approaching and the players needed to collect a certain amount of crystals before they were destroyed by the asteroids. The final cut scene showed the astronauts returning to the colony with the crystals, having accomplished the mission.

The non-fantasy version of the game, developed to compare the effects of fantasy in the effectiveness and engagement of the game, was designed to include the same atomic structure and level design as the fantasy version, but every fantasy element was removed (Figure IV.6). For this non-fantasy version we also used Dickey's principles, but now as a guide to define what should not be included:

- *Create a backstory:* there was no backstory in this version of the game; players took control of electric charges, and were told to move a test charge using the physical laws, without any story-based justification.

- *Establish the physical, temporal, environmental, emotional, and ethical dimensions of the environment*: the environment was visually modified to eliminate any relation with the original story. The players' avatars, the test charges and the obstacles were represented with abstract symbols, and minimalistic black and white graphics were used. All sound effects and music in the game were removed.

- *Present the initial challenge:* because there was no back story, an initial challenge was not presented. The players were only told what to do at each level, but with no far-reaching goal to achieve.

- *Identify potential obstacles and develop puzzles, minor challenges, and resources:* these elements were identified but only in the abstract context in which the objects were presented, and with no relation to a story or justification.

- *Identify and establish roles:* in this version, players did not take the role of astronauts, they directly controlled charges.

- *Develop cut scenes to support the development of the narrative story line:* every cut scene was removed from this version.

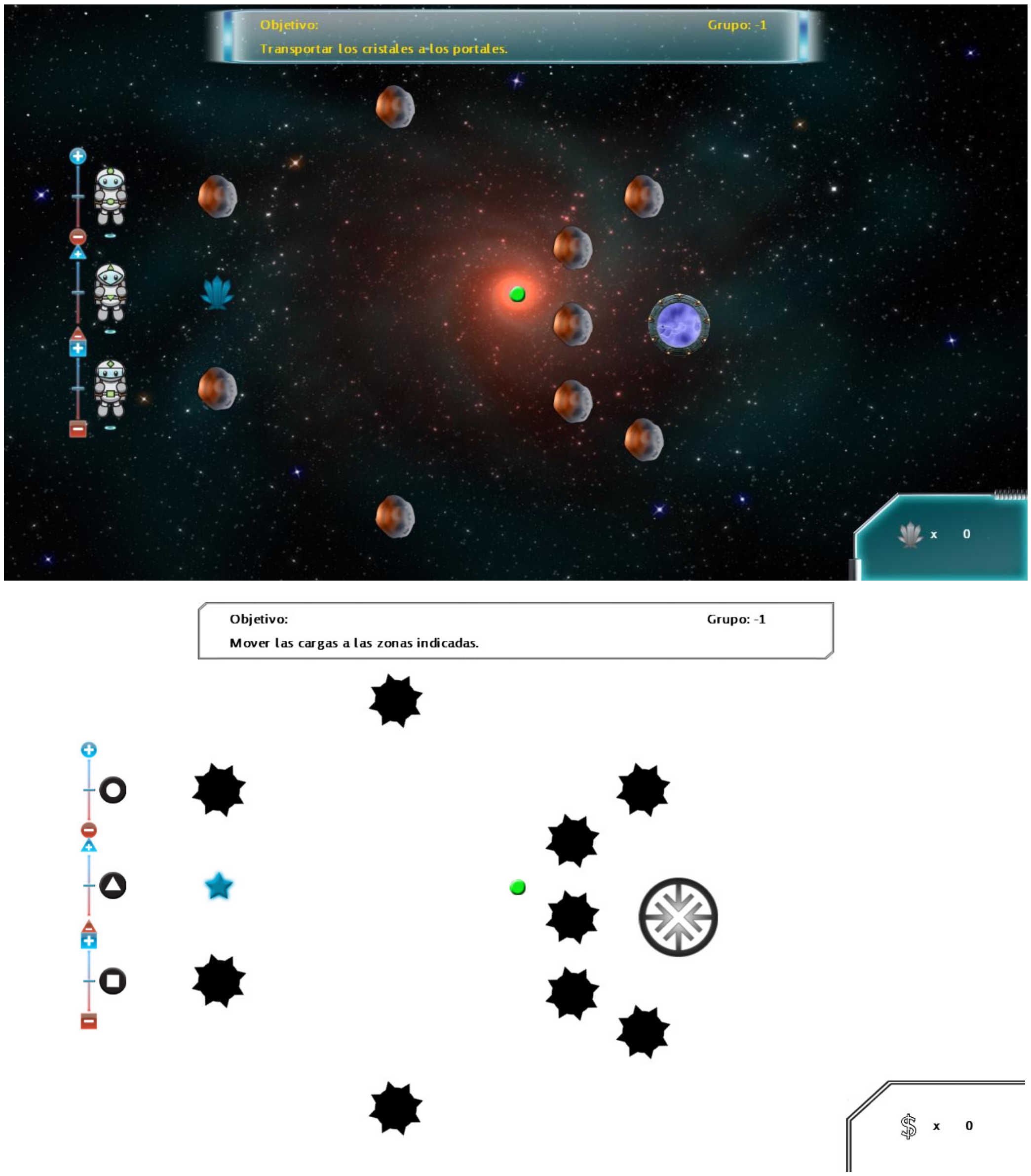

Figure IV.6. Screen shots of the same level viewed in the fantasy version of the game (top) and the non-fantasy version of the game (bottom).

3. Experimental study

3.1 Setup

We designed a two-part experiment in order to answer the two research questions at the heart of this study: (1) does the Atomic Intrinsic Integration Approach improve the educational effectiveness of a conceptual physics game? and (2) does the presence of a fantasy context in a conceptual physics game improve the educational effectiveness or the player engagement? The experiment was carried out in the same public school as the original experiment in Santiago, Chile. The game was tested with 36 12^{th} grade students (27 boys and 9 girls) in one and a half hour long sessions. In each session 9 students played, divided into groups of three that were randomly assigned, and one of our researchers acted as teacher for the session.

The first part of the experiment was designed to answer the first research question. To accomplish this, all students in the sample (36 students) played the version of the game that had been redesigned applying the two intrinsic integration principles. The sample of students that played the original version was assumed comparable, considering that both groups were from the same school and same school year. To answer the second research question, we divided the 36 students into two groups – 20 (14 boys, 6 girls) students from the sample played the fantasy version of the game while the other 16 (3 boys, 3 girls) played the non-fantasy version. To form these two groups, students were randomly sampled from the original 36 and assigned to one of the versions. All experimental groups (original version, fantasy and non-fantasy) were in the same age bracket (17 to 18), and had similar previous experience with games. This experience was assessed through means of a questionnaire before beginning the experiments.

A pre-post test design was used to compare the learning achieved through the game. The instrument used to measure the expected learning outcomes was a specially designed conceptual evaluation that assessed each outcome by asking specific questions (Appendix

A). The evaluation was based on the Conceptual Survey of Electricity (CSE) proposed by Maloney et al. (2001), with certain modifications to ensure that all of the desired learning outcomes were covered and any questions on unrelated or more advanced subjects were excluded. The resulting instrument consisted of 21 questions, with 9 questions taken directly from the CSE, and the rest formulated by two 12th grade physics teachers. The test was validated with 20 students of the same school and year, yielding a Cronbach's alpha of 0.74, above the minimum value of 0.7 required to prove reliability.

To measure the engagement of players we used the Game Experience Questionnaire (GEQ) (IJsselsteijn, Poels, & de Kort, 2008; Appendix B), a questionnaire that has been validated as an effective tool for assessing experiences with both instructional and commercial games. For the purpose of this study, the GEQ was used mainly as a general metric to compare the game experience of the two versions (fantasy and non-fantasy), and not as a way to evaluate specific details of the games. We translated the English version of the questionnaire into Spanish, using the procedure specified by the developers of the questionnaire (IJsselsteijn et al, 2008), in order to maintain valid results for comparison. This questionnaire uses 42 Likert-type questions to measure seven relevant characteristics of the player experience: *competence*, *immersion*, *flow*, *tension*, *challenge*, *negative affect* and *positive affect*. Each one of these characteristics is associated to a subset of items, and is measured with a score from 0 to 4. A higher score is considered better for every characteristic, except for *negative affect* where a lower score is considered a better result. A representative item for each dimension is shown in Table IV.1.

Table IV.1. Representative items for each of the dimensions of the GEQ.

Dimensions	Items
Competence	I was good at it
Immersion	I could use my imagination in the game
Flow	While playing, I forgot about everything around me
Tension	I was nervous during the game
Challenge	I had to put a lot of effort into the game
Negative affect	I found it boring
Positive affect	Playing the game was fun

The experimental procedure was carried out over a three day period. On the first day, all students participating in the study were gathered in a classroom and completed the pre-test during a 30 minute period. On the second day, 4 groups of 9 students participated in the game-based class, which lasted 90 minutes, one group at a time. At the end of the class, students answered the GEQ questionnaire. Finally, on the third day, all students were gathered in a classroom where they had 30 minutes to complete the post-test.

3.2 Session Description

Each session was structured using a script that detailed the flow of the complete videogame-based class. This same script was used in all the sessions and for all version of the videogame, including the original version and the redesigned versions with and without fantasy. One of our researchers acted as the teacher for the session, carrying out this script. Each session started with the teacher giving an introduction to the topic to familiarize students with the general ideas and terminology. This introduction was carried out interactively, asking the students about the basic knowledge on the subject to assess what they already knew. Throughout this introduction the students were already with their corresponding groups and devices, however they could not interact yet with the game because it was paused.

After finishing the introduction, the teacher explained the basic idea of the game, how students should interact with their devices, and its relation to the concepts introduced. The teacher then proceeded to send a message through his laptop to resume the student devices and start the tutorial part of the game. Each tutorial level added a new game element which corresponded to a conceptual element explained by the teacher. The teacher received the results of the student performance in real-time and could pause the game to make specific clarifications. The teacher controlled the flow of the game, advancing to the next tutorial level only when every student had accomplished the minimum requirement. This allowed the teacher to keep the whole class working on the same concepts simultaneously.

After the tutorial phase of the game, the students then played the mission part. This part was collaborative and included different, increasingly difficult levels that encompassed all the relevant instructional concepts, and added additional gameplay challenges. In this part, there was no general explanation provided by the teacher, rather he moved around the room to observe the different groups and answered questions when the students were confused. Similar to the tutorial levels, the students controlled the flow of mission levels, advancing only when all groups had accomplished the minimum goal for the level.

3.3 Results and Statistical Analysis

The results of the conceptual evaluation pre- and post-tests (both of which had a minimum score of 0 and maximum of 21) showed an increase in the average number of correct answers from 7.36 to 12.36, with standard deviations of 2.69 and 3.77 respectively. To analyze the statistical significance of these results we performed a Student's t test for dependant variables, the null hypothesis being that the pre-test and post-test averages were equal and the alternative hypothesis that the post-test average was greater than the pre-test average. To reject the null hypothesis, a one-tailed test was used with a significance level (alpha) of 0.01 (1%). The results of the t test rejecting the null hypothesis were statistically significant ($p < 0.00001$), meaning we can conclude with 99% confidence that the average number of correct answers in the evaluation increases after students are exposed to the game. Additionally, a power analysis was performed to measure the effect size, which resulted in a Cohen's d quantifier value of 1.68 indicating a large effect size. There were no significant differences between boys and girls, and between students with more previous experience with games.

To compare the effects of using the Atomic Intrinsic Integration Approach, we used an ANCOVA analysis with the original experiment's results and the new results, using the pre-test results as co-variable (Table IV.2). The analysis showed that in the enhanced intrinsic integration version of the game, students achieved an average score of 12.11 which was a statistically significant improvement ($F = 4.55$; $p < 0.05$) on the average score of 10.32 obtained with the original version. This implies that, on average, students learned more with the redesigned version of the game. Two additional ANCOVA analyses were performed per gender, also obtaining significant differences for boys ($F=4.22$; $p <0.05$) but no significant difference for girls ($F=0.69$; $p=0.41$). This suggested that the modifications were more useful for boys than for girls.

Table IV.2. Test results of comparison between original game and the atomic intrinsic integration version

	Gender	Original Game		Atomic Intrinsic Integration Game	
Test		Mean	Std. Dev.	Mean	Std. Dev.
Pre-test	Boys	6.69	1.88	7.22	2.72
	Girls	5.57	2.47	7.77	2.72
	Total	**6.11**	**2.24**	**7.36**	**2.69**
Post-test	Boys	9.61	2.72	12.40	4.18
	Girls	10.35	2.81	12.22	2.33
	Total	**10.00**	**2.74**	**12.36**	**3.77**
Adjusted Post-test	Boys	9.92	-	12.35	-
	Girls	10.77	-	11.88	-
	Total	**10.32**	**-**	**12.11**	**-**

To understand how well each physical law was understood by the students - a serious problem with the original version of the game - we measured the percentage of students who increased their test scores from the pre-test to the post-test, in questions related to each physical law. The percentage of students which improved after playing the new game in questions related to Coulomb's law and the principle of linear superposition increased from 66.66% to 83.33% and 62.07% to 81.56% respectively. This shows that the new version of the game increased the number of students that improved their performance after playing the game.

To compare the effects of the fantasy element in the game we used an ANCOVA analysis with the results of both the fantasy and non-fantasy groups, using the pre-test results as co-variable (Table IV.3). The analysis showed that there were no statistically significant differences between the results obtained by the students who played the fantasy and non-fantasy game (F = 0.30; p = 0.58). Two additional ANCOVA analyses were performed per gender, obtaining no significant differences for boys (F=0.47; p=0.49) or girls (F=0.18; p=0.68).

Table IV.3. Test results of comparison between fantasy and non-fantasy versions of the game

	Gender	Endogenous Fantasy Game		Non-Fantasy Game	
Test		Mean	Std. Dev.	Mean	Std. Dev.
Pre-test	Boys	6.87	3.05	7.61	2.36
	Girls	8.5	2.12	7.57	2.99
	Total	**7.06**	**2.95**	**7.60**	**2.52**
Post-test	Boys	11.64	4.03	13.23	4.34
	Girls	13	2.82	12	2.38
	Total	**11.81**	**3.85**	**12.80**	**3.75**
Adjusted Post-test	Boys	11.95	-	12.90	-
	Girls	12.92	-	12.02	-
	Total	**12.01**	**-**	**12.64**	-

The results of the Game Experience Questionnaire for students that played the fantasy and non-fantasy versions (Figure IV.7) show that students from both groups achieved similar results in all of the dimensions measured. To analyze the statistical significance of these results, for each dimension of the GEQ we performed a Student's t test for independent variables, the null hypothesis being that the score of each dimension for both versions would be equal and the alternative hypothesis that the scores would be different. To reject the null hypothesis, a two-tailed test was used with a significance level (alpha) of 0.05 (5%). The results of the t test for every dimension were not statistically significant, meaning that we cannot reject the null hypothesis of the scores being equal. Considering the GEQ scores in all dimensions as a general metric for the player experience, these results suggest that there was no significant difference in the player's experience of the fantasy version and the non-fantasy version.

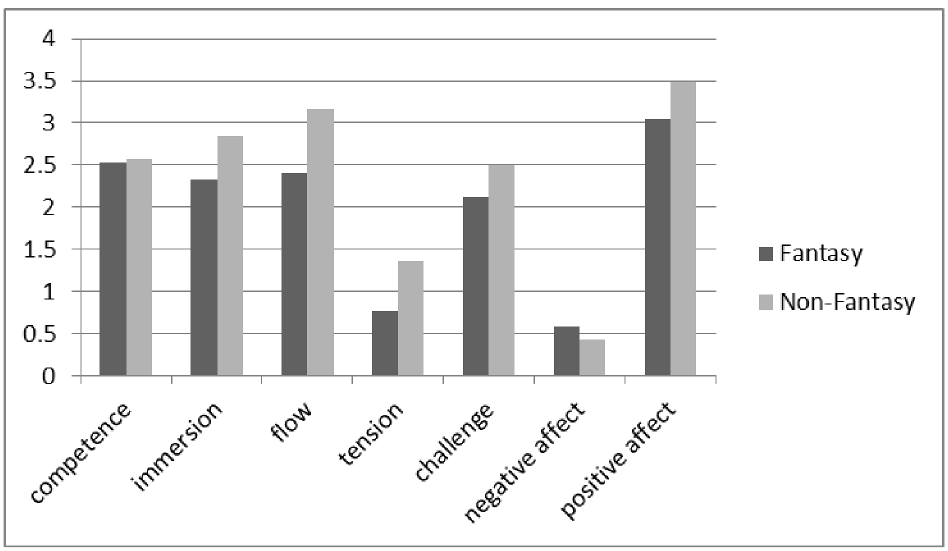

Figure IV.7. Game experience questionnaire results of comparison between fantasy and non-fantasy versions of the game

4. Discussion

The results of the experimental study show that applying the Atomic Intrinsic Integration Approach was useful for increasing the average test results and decreasing the number of students with conceptual problems. Intrinsic integration provided a useful methodology for understanding what elements should be improved in the game, while the atomic analysis helped visualize how the interaction was structured in the game, and how this structure should be modified to improve the game.

Fantasy did not play a relevant role in the educational effectiveness of the game, with no significant differences between the two versions of the game in the pre-post test comparison. A more surprising result was that in the game experience questionnaire there were also no significant differences between both games. This suggests that the fantasy element did not contribute to engaging the players. However, it is difficult to generalize these results for other contexts because of the different ways that fantasy can be included in the game and also because the relative importance of the fantasy element will vary depending on the type of game.

Based on this experience, we outline some principles below that describe how the Atomic Intrinsic Integration Approach should be applied when designing games for the conceptual understanding of physics:

(1) Give the player control of every relevant independent variable in the simulation as a low-level game atom, and introduce them progressively throughout the game

Although this principle was already included in the original version, we believe it is an essential aspect when designing this type of game and is consistent with previous experiments with interactive simulations for physics (Adams, 2008). These should be combined with a progressive introduction of each variable, allowing the player to directly experience how each variable independently affects the results of the simulation. These relevant variables should be included as operative mechanics, by linking a player input with an explicit representation, which ideally should be tightly integrated within the game world, and not through external numeric displays.

(2) Provide appropriate explicit representations using a game atom for the simulated dependent variable integrated within the game world, which serve as scaffolding to increase the players understanding. Progressively remove these scaffolds as the game advances, to test the ability of the players to apply their knowledge by themselves without help.

One fundamental difference between the original and new version of the games was the inclusion of arrows to symbolize forces. The two physical laws represented in the game were related to the concept of force, and this was not directly represented in the original version. This was especially problematic for understanding the principle of linear superposition, which involves vector addition, and it is very hard to understand without a clear representation.

The addition of the arrows helped the students to complete the feedback loop between their actions (which modified the independent variables) and the result (which simulated the dependent variables), and thus increased their conceptual understanding. It is also essential that the representation used is appropriate for the task: if we had used number values to represent the forces instead of visual arrows, the players would not as easily have understood the concept of vector addition applied to force. What is considered an "appropriate representation" should be analyzed case by case, depending on the concept.

It is also essential to eventually remove the scaffolding provided by this representation. If this is not done there is a real danger that the players will interact by mere trial and error and will not reflect on how the independent variables affect the simulation.

(3) Connect the dependent variables that result from the simulated principles with the goal of the game through a game atom that creates an interesting and fun challenge.

The main learning objective of the game was for the players to understand how the independent variable of each law affected its result. This is the main cognitive challenge for the players, but on its own it does not generate a fun game. Even when an additional but simple challenge is added, like in the first version of the game where they had to apply forces to move the crystals, it was not enough to create an interesting and engaging game. Thus to create an engaging instructional game, it is essential to design a challenge structure on top of the instructional structure, by connecting the output of the simulation with an interesting challenge. In the case of this game, by adding different obstacles through increasingly complex levels we achieve the necessary engagement among players. Because the challenge was interesting and it required the player to master the use of the electrical force, the students were motivated to reflect on the relationship between the different variables involved in all of the physical laws.

How to identify an interesting challenge is something that cannot be pre-specified, and must be play-tested for each specific game. This in essence is what game designers do best - carefully crafting interactions that are both engaging and fun for the player. What is different for this type of game is that the interesting challenges must be semantically linked to the simulated result, in such a way that the complete structure of the game feels natural and produces a successful flow experience. As our experimental results suggest, if the challenge provided is sufficiently interesting and fun, secondary elements of the game, such as a fantasy element, can be excluded without decreasing player engagement.

A summary of these three principles is presented in figure IV.8, showing the generic structure of a game that is designed using the principles.

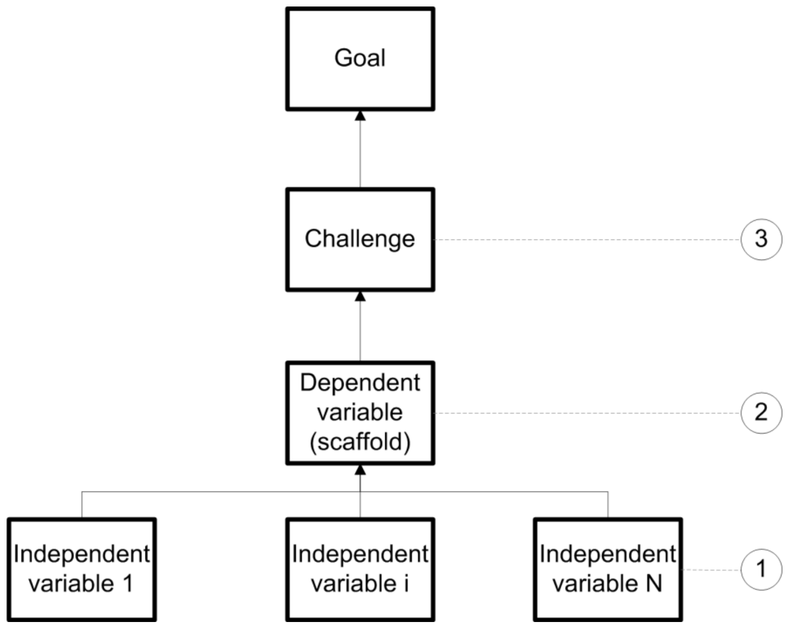

Figure IV.8. Generic structure of a game for the conceptual understanding of physics applying the three principles of our methodology: (1) the independent variables of the simulation are integrated as low-level game atoms, (2) the dependent variable of the simulation is integrated as a scaffolded game atom, (3) this connects to the goal through an additional game atom that provides an interesting challenge.

5. Conclusions and Future work

Using the principles presented in the previous section, we have defined one possible methodology for the design of games to assist with the conceptual understanding of physics. We believe that these principles can be applied to many physical laws and processes, and that they provide a simple and useful guide. Further experimental work should be carried out in other physical domains in order to validate these principles.

There are many questions outside of the scope of this study that are left to be answered by future work. Firstly, it is not clear why the redesigned version significantly increased boys' results but not the girls'. Further analysis and experiments are needed to understand why this difference exists. Also, further analysis of the results from the GEQ is required to understand how the scores of each specific dimension could be used to improve the game. Finally, the relevance of a fantasy component in this and other types of games should be further studied. Adding a story implies more effort in designing a good game, so it is important to know how relevant it is for different types of games.

One important difference between traditional game design and instructional game design is that in the former there are no initial restrictions beyond the budget and imagination of the designer. In instructional games, on the other hand, there are several restrictions regarding learning outcomes and instructional methodology. Principles such as those presented here facilitate the task of the game designer by providing a systematic way of incorporating these restrictions into the game design.

Although some of these principles could well be applied to other domains we think that this should be considered carefully beforehand. A general problem with instructional games is thinking that general principles can be applied undifferentiated to any type of instructional game and every domain. A goal for the instructional game community should be to define guidelines and principles that are appropriate to specific situations and domains, and validate them through continuous experiments in realistic conditions, in order to generate tools and methods that facilitate the design of more engaging and effective games.

V. CONCLUSIONS

The research presented in this thesis advocates the view that videogames can be a useful teaching tool for improving the conceptual understanding of Physics, if they are integrated into the classroom using a pedagogical model that supports the intervention. As it is with any other educational tool, videogames are no “silver bullet” and they should be applied in the context and scenarios where they can add value over other methodologies, taking advantage of their unique affordances. Moreover, the design of a videogame for classroom teaching must also take in account all the other factors required to orchestrate a successful educational intervention including the pedagogical model used to structure the class and the optimal technological platform for the deployment of the videogame.

Designing educational videogames with specific learning objectives and integrating them in a classroom is a very difficult task, because it requires expertise in several disciplines: learning science, to understand how to structure the videogame as a classroom learning environment; game design, to understand how to create an engaging experience; and the particular domain of knowledge that the videogame will teach (in the case of this project, Physics), to understand the concepts of the field of study itself and the associated pedagogy. Regarding this complex problem, an important contribution of this thesis is the validation of the design-based research methodology as an effective way of developing an engaging and educationally effective videogame. The iterative nature of the methodology allows the exploration of the multiple aspects involved in this type of design problems, which, as the results of Chapter III shows, can help to improve the effectiveness of a videogame-based class.

Another relevant contribution of this project is the development of innovative technological platforms for the deployment of collaborative videogames in the classroom. An essential component for integrating effective learning environments is to choose the right technological platform to support it. By designing different platforms and comparing their impact for the deployment of the same videogame, this project has shown the multidimensional nature of the problem of designing and integrating videogames in the classroom, which should take into account not only the logic and progression of the game mechanics, but also the effects that different input devices and display representations can have on the learners. The gender difference discovered in the comparative analysis detailed in Chapter II show one of the possible scenarios where these differences, that are beyond the core elements of the game, have a serious impact in the learning experience as a whole.

This thesis also provides contributions regarding the design of engaging educational videogames. Although there is no magic recipe for creating engaging videogames, understanding what are the possible sources of this engagement is essential to taking advantage of the motivational aspect of videogames. The intrinsic integration model cited in Chapter III (Habgood & Ainsworth, 2011) describes what should ideally be aspired when designing an educational videogame: that the act of learning itself can be seamlessly integrated with the act of playing the videogame mechanics, which then becomes the main source of engagement. However, additional sources of engagement should also be considered as a way of complementing this core engagement through the game mechanics. The social aspects of videogames, both collaboration and competition, can be a very powerful motivator, something which was observed in all the classroom experiments of this project. And, although the comparative analysis in Chapter III showed no improvement in engagement because of the fantasy context for the videogame of this project, this does not imply that fantasy can't be used as an engagement mechanism in other contexts. Creating an engaging experience is complex and dependent on the individual characteristics of each player, which suggest that all of these different sources of engagement should be considered if the goal is to motivate every student.

VI. FUTURE WORK

The experimental results obtained in this thesis are valid only for the specific subjects (Chilean highschool students), physics principles (Coulomb's Law, Law of Action and Reaction, Principle of Linear Superposition of Forces) and pedagogical model (Computer Supported Collaborative Learning) used during the project. These three dimensions should be explored further to understand how the different results vary when one or more of these aspects are modified. Subjects of different characteristics (age, culture, etc.) should participate in the same videogame-based class to understand how subject variation modifies the results obtained. Regarding the physics principles, the methodology proposed in Chapter III needs to be applied for other physical laws in order to understand its usefulness. And finally, although CSCL was used throughout the whole project, it is not clear what are the advantages or disadvantages of using such model for this specific videogame, and whether the collaborative mechanics designed are adequate for learning these principles. An interesting follow-up study is to compare an individual version of the videogame with the collaborative one, and analyze how both learning and engagement are affected.

An additional area of further study is to compare the usage of classroom videogames to teach physics conceptually with other methodologies that are currently being used successfully with the same purpose such as Peer Instruction (Mazur, 1997). The effort of developing a videogame is significant, so it would be useful to understand in which specific cases and for which specific physic principles it represents and advantage over simpler methodologies.

The technological platforms designed for this project should be further tested with different co-located collaborative videogames in order to understand which scenarios and learning objectives are they best suited for. Additional platforms that use different input devices or display technologies should also be explored in order to develop a general picture of the space of possibilities for this type of videogames. One possible way of achieving this is by defining a taxonomy of co-located collaborative platforms for videogames, which can then be used to explore in a structured way what has been done in this space and what else is left to create.

Although the augmented reality platform didn't add concrete value in the context of the experiments performed and the measurements taken, it is not clear if the immersive nature of the platform adds some unmeasured value, for example in long term learning. The same can be said for the fantasy context of the videogame. It may be the case that by creating a more memorable experience through an immersive interface or a narrative context, students can achieve higher long term retention of the concepts, so this is something that should also be studied further.

Finally, although this project considered a basic level of orchestration for the interventions tested, there is plenty of room for improvement in this aspect. A complete and realistic orchestration model should include additional elements such as involving real teachers and training them to use the tool, integrating non-digital content with the videogame-base class and understanding how to fit the intervention into a predefined lesson plan. All this elements were beyond the scope of this project, but can be explored in the future to understand the practical feasibility of using this type of videogames as a tool for educators.

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APPENDICES

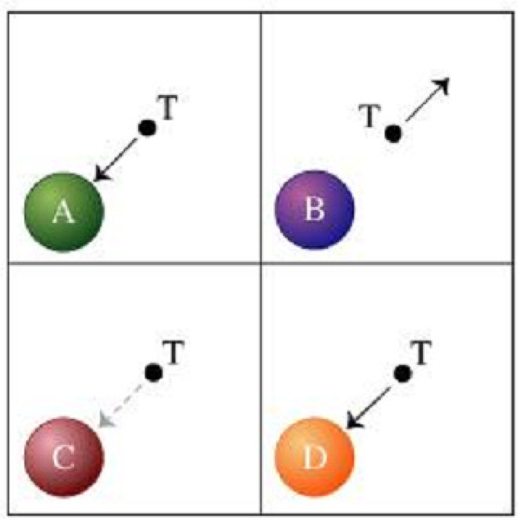
APPENDIX A: CONCEPTUAL TEST OF ELECTROSTATICS

The following test is the modified version of the Conceptual Survey of Electromagnetism (Maloney et al, 2001) used in the experiments of chapter II, III and IV.

1. Dos objetos cargados positivamente están separados por una distancia *d*. La primera carga es mayor en magnitud que la segunda.

(a) La primera carga ejerce una fuerza mayor en la segunda carga.
(b) La segunda carga ejerce una fuerza mayor en la primera carga.
(c) Las cargas se ejercen mutuamente fuerzas iguales en magnitud y de sentido opuesto.
(d) Las cargas se ejercen mutuamente fuerzas iguales en magnitud y en el mismo sentido.
(e) Ninguna de las anteriores

Para las preguntas 2-4:
Se tienen cuatro partículas cargadas denominadas A, B, C y D. Una carga positiva de prueba (T) experimenta las fuerzas indicadas en la figura cuando es acercada a cada una de las partículas: la carga de prueba T es fuertemente atraída por A, fuertemente repelida por B, débilmente atraída por C y fuertemente atraída por D.



2. ¿Cuál es la naturaleza de la fuerza entre las partículas A y B?

(a) fuertemente atractiva
(b) fuertemente repulsiva
(c) débilmente atractiva
(d) ni atractiva ni repulsiva
(e) ninguna de las anteriores

3. ¿Cuál es la naturaleza de la fuerza entre las partículas A y D?

(a) fuertemente atractiva
(b) fuertemente repulsiva
(c) débilmente atractiva
(d) ni atractiva ni repulsiva
(e) ninguna de las anteriores

4. ¿Cuál es la naturaleza de la fuerza entre las partículas A y C?
(a) atractiva
(b) repulsiva
(c) ni atractiva ni repulsiva
(d) no hay suficiente información para determinarlo
(e) ninguna de las anteriores

Para las preguntas 5-7:
Dos objetos pequeños, cada uno con una carga de +Q se ejercen mutuamente una fuerza de magnitud F.

Reemplazamos uno de los objetos por otro cuya carga es +4Q:

5. La magnitud original de la fuerza en la carga +Q era F; ¿cuál es la magnitud en +Q ahora?

(a) 16F (b) 4F (c) F (d) F/4 (e) otra

6. ¿Cuál es la magnitud de la fuerza en la carga +4Q?

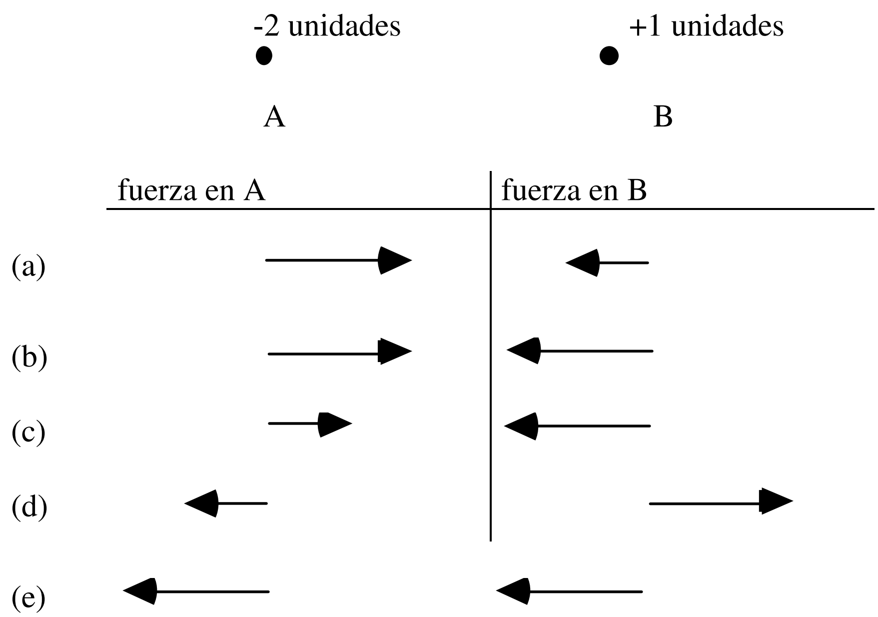
(a) 16F (b) 4F (c) F (d) F/4 (e) otra

Luego movemos ambas cargas para estar a una distancia 3 veces la distancia original:

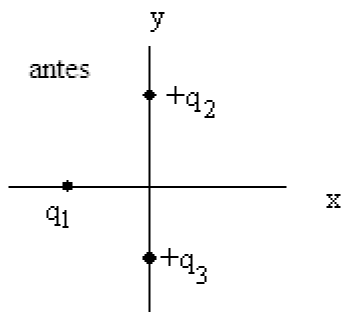
7. ¿Cuál es ahora la magnitud de la fuerza sobre la carga +4Q?

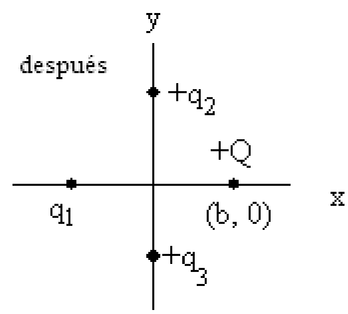
(a) F/9 (b) F/3 (c) 4F/9 (d) 4F/3 (e) otra

8. La figura a continuación muestra una partícula (denominada B) que tiene una carga eléctrica neta de +1 unidades. Varios centímetros a la izquierda hay otra partícula (denominada A) que tiene una carga neta de -2 unidades. Elija el par de vectores de fuerza (indicados por las flechas) que correctamente comparen la fuerza eléctrica en A (producida por B) con la fuerza eléctrica en B (producida por A).



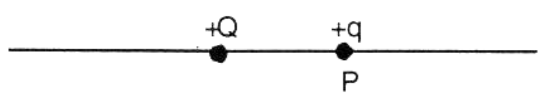
9. En la figura a continuación, cargas positivas q2 y q3 ejercen sobre q1 una fuerza eléctrica neta en el eje +x. Si una carga positiva Q es agregada en (b,0), ¿qué pasará ahora con la fuerza en q1? (Todas las cargas están fijas en sus ubicaciones).





(a) No hay cambio en la magnitud de la fuerza neta, dado que Q esta en el eje x.
(b) La magnitud de la fuerza neta cambiará, pero no la dirección.
(c) La magnitud de la fuerza neta disminuirá y la dirección puede cambiar por la interacción entre Q y las cargas positivas q2 y q3.
(d) La magnitud de la fuerza neta aumentará y la dirección puede cambiar por la interacción entre Q y las cargas positivas q2 y q3.
(e) No se puede determinar sin saber la magnitud de q1 y/o Q.

10. La figura muestra una carga positiva +Q. Una segunda carga positiva, colocada en el punto P, no experimenta fuerza neta. Si tuviésemos las magnitudes de carga adecuadas, ¿cuál de las siguientes situaciones podría producir esta situación?

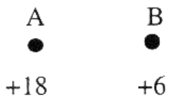


(a) Una carga positiva colocada a la derecha de P.
(b) Una carga negativa colocada a la derecha de P.
(c) Una carga positiva colocada a la izquierda de P.
(d) Una carga negativa colocada a la izquierda de P.
(e) Ambas (a) y (d) podrían producir esta situación.

11. Las figuras a continuación muestran 3 situaciones donde dos cargas eléctricas están separadas por una misma pequeña distancia. Todas las cargas eléctricas ejercen fuerza entre sí. ¿En cuál de las figures la carga A ejerce una fuerza sobre B mayor que la fuerza que ejerce B sobre A?

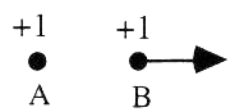
(a) 

(b) 

(c) 

(d) A y B se ejercen fuerzas iguales entre sí en todos los casos.
(e) La fuerza que A ejerce sobre B es mayor en (a) y (c), pero menor en (b).

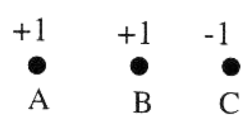
Para las preguntas 12-17



La imagen superior muestra una partícula (denominada B) que tiene una carga eléctrica neta de +1 unidad. Un centímetro a la izquierda hay otra partícula (denominada A) que también tiene una carga neta de +1 unidad. La flecha representa el tamaño y la dirección de la fuerza eléctrica experimentada por B (provocada por la presencia de A).

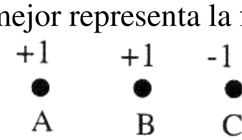
En las siguientes preguntas, tres o cuatro partículas cargadas son colocadas a una distancia de un centímetro, con la unidad y signo de la carga indicado. Cada una de las cargas está sujeta a la fuerza eléctrica provocada por las otras partículas.

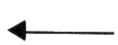
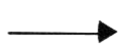
12. ¿Cuál de las siguientes flechas mejor representa la fuerza neta sobre la carga B?



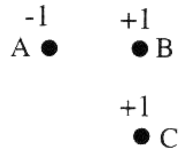
(a)  (b)  (c)  (d)  (e) cero

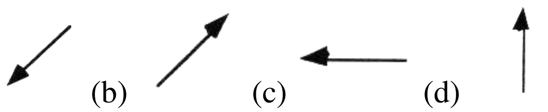
13. ¿Cuál de las siguientes flechas mejor representa la fuerza neta sobre la carga C?



(a)  (b)  (c)  (d)  (e) cero

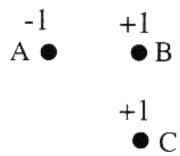
14. ¿Cuál de las siguientes flechas mejor representa la fuerza neta sobre la carga B?





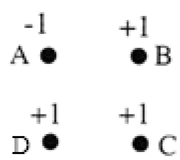
(a) (b) (c) (d) (e) ninguna de estas

15. ¿Cuál de las siguientes flechas mejor representa la fuerza neta sobre la carga C?



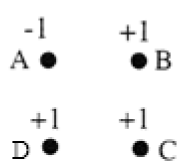
(a) (b) (c) (d) (e) una flecha en alguno de los ejes

16. ¿Cuál de las siguientes flechas mejor representa la fuerza neta sobre la carga A?



(a) (b) (c) (d) (e) ninguna de estas.

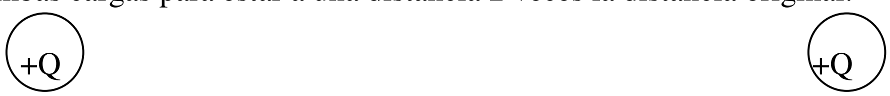
17. ¿Cuál de las siguientes flechas mejor representa la fuerza neta sobre la carga C?



(a)  (b)  (c)  (d)  (e) ninguna de estas.

Para las preguntas 18 -21:
Dos objetos pequeños, cada uno con una carga de +Q se ejercen mutuamente una fuerza de magnitud F.

Movemos ambas cargas para estar a una distancia 2 veces la distancia original:



18. La magnitud original de la fuerza en la carga de la izquierda era F; ¿cuál es la magnitud en esa carga ahora?

(a) 2F (b) 4F (c) F/2 (d) F/4 (e) otra

19. ¿Cuál es la magnitud de la fuerza en la carga de la derecha?

(a) 2F (b) 4F (c) F/2 (d) F/4 (e) otra

Reemplazamos uno de los objetos por otro cuya carga es -Q:

20. ¿Cuál es ahora la magnitud de la fuerza sobre la carga +Q?

(a) 8F (b) F/4 (c) 0 (d) 4F (e) otra

21. ¿Cuál es la dirección de la fuerza sobre la carga +Q?

(a)  (b)  (c)  (d) ninguna, la magnitud es 0 (e) otra

APPENDIX B: GAME EXPERIENCE QUESTIONNAIRE

The following questionnaire is the translate version of the Game Experience Questionnaire (IJsselsteijn et al, 2008) used in the experiments of chapter IV.

Por favor indica para los siguientes items como te sentiste al jugar el juego, ocupando la siguiente escala:

Para nada	Un poco	Moderadamente	Bastante	Extremadamente
0	1	2	3	4
< >	< >	< >	< >	< >

1 Me sentí satisfecho

2 Me sentí hábil

3 Estaba interesado en la historia del juego

4 Pude reirme del juego

5 Me sentí completamente absorto

6 Me sentí feliz

7 Me sentí tenso

8 Sentí que estaba aprendiendo

9 Me sentí inquieto

10 Pensé en otras cosas

11 Lo encontré cansador

12 Me sentí fuerte

13 Pensé que era difícil

14 Era estéticamente agradable

15 Me olvidé de todo lo que estaba a mi alrededor

16 Me sentí bien

17 Sentí que yo era bueno para jugarlo

18 Me sentí aburrido

19 Me sentí exitoso

20 Me sentí imaginativo

21 Sentí que podría explorar cosas

22 Lo disfruté

23 Fui rápido en alcanzar los objetivos del juego
24 Me sentí molesto
25 Me distraje
26 Me sentí estimulado
27 Me sentí irritable
28 Perdí la noción del tiempo
29 Me sentí desafiado
30 Me pareció impresionante
31 Estuve profundamente concentrado en el juego
32 Me sentí frustrado
33 Me pareció una experiencia muy variada
34 Perdí la conexión con el mundo exterior
35 Me aburrió la historia
36 Tuve que poner mucho esfuerzo
37 Sentí la presión del tiempo
38 Me provocó un mal estado de animo
39 Me sentí presionado
40 Estuve totalmente ocupado con el juego
41 Lo encontré entretenido
42 Me sentí competente

APPENDIX C: ARTICLE ACCEPTANCE CONFIRMATION

The following message is an acceptance confirmation from Computers & Education, acknowledging that the article presented on chapter II of this thesis, entitled "A framework for the design and integration of collaborative games inside the classroom", has been accepted for publication.

Alejandro Echeverria <alejandro.echev@gmail.com>

Decision on your submission - CAE-D-10-00627R2

Computers & Education <cae@elsevier.com> Fri, Dec 24, 2010 at 11:14 AM
To: alejandro@echev.com
Cc: cctsai@mail.ntust.edu.tw

Ms. Ref. No.: CAE-D-10-00627R2
Title: A framework for the design and integration of collaborative classroom games
Computers & Education

Dear Mr. Alejandro Echeverria,

Congratulations, your paper, A framework for the design and integration of collaborative classroom games, is accepted for publication in Computers & Education, and shall shortly be available online prior to typesetting and proofreading to ensure your research reaches readers as soon as possible.

We hope you will consider submitting similarly high quality work to Computers & Education in the future, and that we may rely on you to act as a peer reviewer of other papers submitted to the journal.

Again, thank you for submitting your work to Computers & Education.

Yours truly,

Chin-Chung Tsai
Co-Editor
Computers & Education

Comments from the Editor:
I still found some minor language problems for the paper. Please carefully read the whole paper again when receiving paper proofs.

APPENDIX D: ARTICLE ACCEPTANCE CONFIRMATION

The following message is an acceptance confirmation from Computers in Human Behaviour, acknowledging that the article presented on chapter III of this thesis, entitled “Exploring different technological platforms for supporting co-located collaborative games in the classroom”, has been accepted for publication.

Alejandro Echeverria <alejandro.echev@gmail.com>

Your Submission CHB-D-11-00497R1

Bob Tennyson <rdtennyson@gmail.com> Mon, Jan 30, 2012 at 12:05 PM
To: aaecheve@uc.cl

Ms. Ref. No.: CHB-D-11-00497R1
Title: Exploring different technological platforms for supporting co-located collaborative games in the classroom
Computers in Human Behavior

Dear Mr. Alejandro Echeverria,

I am very pleased to inform you that your paper "Exploring different technological platforms for supporting co-located collaborative games in the classroom" has now been fully accepted for publication in Computers in Human Behavior. Congratulations!

Many thanks for submitting your work to this journal.

With kind regards,

Bob D. Tennyson
Editor
Computers in Human Behavior

APPENDIX E: ARTICLE ACCEPTANCE CONFIRMATION

The following message is an acceptance confirmation from Computers & Education, acknowledging that the article presented on chapter IV of this thesis, entitled "The atomic intrinsic integration approach: A structured methodology for the design of games for the conceptual understanding of physics", has been accepted for publication.

Alejandro Echeverria <alejandro.echev@gmail.com>

Decision on your submission - CAE-D-11-00829R2

Computers & Education <cae@elsevier.com> Wed, Mar 28, 2012 at 10:12 AM
To: alejandro@echev.com
Cc: cctsai@mail.ntust.edu.tw

Ms. Ref. No.: CAE-D-11-00829R2
Title: The Atomic Intrinsic Integration Approach: A structured methodology for the design of games for the conceptual understanding of physics
Computers & Education

Dear Mr. Alejandro Echeverria,

Congratulations, your paper, The Atomic Intrinsic Integration Approach: A structured methodology for the design of games for the conceptual understanding of physics, is accepted for publication in Computers & Education, and shall shortly be available online prior to typesetting and proofreading to ensure your research reaches readers as soon as possible.

We hope you will consider submitting similarly high quality work to Computers & Education in the future, and that we may rely on you to act as a peer reviewer of other papers submitted to the journal.

Again, thank you for submitting your work to Computers & Education.

Yours truly,

Chin-Chung Tsai
Co-Editor
Computers & Education

Comments from the Editors and Reviewers:
The authors made adequate revisions and responses.

APPENDIX F: ADDITIONAL EXPERIMENTAL ANALYSIS

The following section presents a detailed exaplanation of the different quasi-experimental studies performed during the project. For each of the experiments presented, we describe the description of the sample used, the specific conditions and context of the experiment, the results obtained and a detailed statistical analysis of the results.

Experiment N°1: First iteration of the videogame, Chapter II

The first experient was performed after the first iteration of the videogame was completed, in June 2010. The goal of this first experiment was to validate that a class using the videogame and the CSCL script would produce learning gains in students for the specific learning objectives.

Sample Description

The first experiment was performed with 12th grade students of a public school from Santiago, Chile, which we will further refer as school A. School A had a 4th grade SIMCE average of 286 in 2011. All the students that participated in the experiment belonged to the same class, which corresponded to the scientific/mathematic class of that school A. From all the students of that class 27 were randomly selected to participate in the study, 13 male and 14 female. The 27 selected students were then randomly assigned in thre groups of 9, each group participating in a different videogame session.

Experimental Setup

The experiment was carried out in three different sessions, each one with duration of 2 hours. In each session one of the three groups of 9 students participated. All the sessions were performed in the same classroom of school A.

Each session had the following structure:

- Students answered the conceptual survey of electrostatics (Appendix A) and a questionnaire detailing their previous experience with technology and videogames (30 minutes).
- The 9 students were randomy assigned in three groups of three students. One of the researchers takes the role of the teacher and follows the class script. Throughout the session, students play the different individual levels of the videogame first and then the collaborative levels with their respective groups (1 hour).
- Students answered the conceptual survey of electrostatics (Appendix A) (30 minutes).

Results and Statistical Analysis

The results of the conceptual evaluation pre- and post-tests showed an increase in the average number of correct answers from 6.11 to 10, with standard deviations of 2.24 and 2.74 respectively. A Kolmogorov-Smirnov test of normality was performed on both pre- and post-test results, and in both cases the normality assumption was fullfilled.

A paired-samples t-test was conducted to evaluate the impact of the intervention on scores on the conceptual survey. There was a statistically significant increase in scores comparing the pre- ($M=6.11$, $SD=2.24$) and post-test [$M=10.00$, $SD=2.74$, $t(26)=-5.75$, $p<.0005$]. The eta squared statistic (.55) indicated a large effect size.

Considering the small sample size used in the experiment, and additional non-parametric test was performed to further validate the result. A Wilcoxon Signed-rank test shows that there is a significant increase between pre- and post-test ($Z = -4.11$, $p < 0.0005$).

The effect of previous experience with technology and video game use was also analyzed. To quantify this factor we utilized the Pearson's correlation coefficient, which measures the linear relationship between two random quantitative variables. The test showed no significant correlation between the number of correct answers and previous experience with either technology (cell phone use: r=-0.3; computer use: r=0.12) or video games (computer games: r=0.06; console games: r=0.16; cell phone games: r=-0.03).

The possibility of a gender effect was controlled for by dividing the sample and analyzing the male and female groups separately. Because of the reduced size of the subsamples, a non-parametric test was used to compare the pre- and post-test results for boht females and males. A Wilcoxon Signed-rank test shows that there is a significant increase between pre- and post-test for both females (Z = -3.04, p = 0.002) and males (Z = -2.88, p = 0.004).

Experiment N°2: Second iteration of the videogame, Chapter III

The second experient was performed after the second iteration of the videogame was completed. The experiment was carried out in two parts: the first part corresponded to the testing of the augmented reality version of the videogame which was done in October 2010; the scond part corresponded to the testing of the multiple mice version of the videogame which was done in June 2011. The goal of this second experiment was to validate that the same videogame class deployed with two different technological platforms would produce learning gains in students for the specific learning objectives; and to compare the learning gains with both platforms.

Sample Description

The second experiment was performed with 11^{th} grade students of a public school from Santiago, Chile, which we will further refer as school B. School B had a 4^{th} grade SIMCE average of 279 in 2011. For the first part of the experiment, all the students that participated in the experiment belonged to the same class, which corresponded to the scientific/mathematic class of 2010 of school B. From all the students of that class 27 were randomly selected to participate in the study, 12 male and 15 female. The 27 selected students were then randomly assigned in thre groups of 9, each group participating in a different videogame session. For the second part of the experiment, all the students that participated in the experiment belonged to the same class, which corresponded to the scientific/mathematic class of 2011 of school B. From all the students of that class 27 were initially randomly selected to participate in the study, which were then randomly assigned in thre groups of 9, each group participating in a different videogame session. However, due to external problems in the school, the third group of 9 students was not able to complete their session, resulting in a final number of 18 students that participated, 12 males, and 5 females.

Experimental Setup

The experiment was carried out in five different sessions, three with the students that played the augmented reality version, and two with the students that played the multiple mice version, each session with duration of 2 hours. In each session one of the groups of 9 students participated. All the sessions were performed in the same classroom of school B.

In every session, the same researcher accomplished the role of the teacher. Also in every session, the same script was used. Both versions of the videogame only differed in the technological platforms: the level progression, level design, and game mechanics were the same.

Each session had the following structure:

- Students answered the conceptual survey of electrostatics (Appendix A) and a questionnaire detailing their previous experience with technology and videogames (30 minutes).
- The 9 students were randomy assigned in three groups of three students. One of the researchers takes the role of the teacher and follows the class script. Throughout the session, students play the different individual levels of the videogame first and then the collaborative levels with their respective groups (1 hour).

- Students answered the conceptual survey of electrostatics (Appendix A) (30 minutes).

Results and Statistical Analysis

The results of the conceptual evaluation pre- and post-tests showed an increase in the average number of correct answers from 4.27 (SD = 1.74) to 6.22 (SD = 3.13) for students who played the multiple mice version, and an increase in the average number of correct answers from 3.51 (SD = 2.04) to 6.37 (SD = 2.89) for students who played the augmented reality version. A Kolmogorov-Smirnov test of normality was performed on both groups, for the pre- and post-test results. For the augmented reality version in both the pre- and post-test the normality assumption was fullfilled. For the multiple mice version, however, only the post-test fullfilled the nornality assumption.

For the augmented reality version of the game, a paired-samples t-test was conducted to evaluate the impact of the intervention on scores on the conceptual survey. There was a statistically significant increase in scores comparing the pre- (M=3.51, SD=2.04) and post-test [M=6.37, SD=2.89, t(26)=-7.47, p<.0005]. The eta squared statistic (.68) indicated a large effect size. Additionally, considering the small sample size used in the experiment, and additional non-parametric test was performed to further validate the result. A Wilcoxon Signed-rank test showed that there was a significant increase between pre- and post-test (Z = -4.27, p < 0.0005).

For the multiple mice version of the game, a paired-samples t-test was conducted to evaluate the impact of the intervention on scores on the conceptual survey. There was a statistically significant increase in scores comparing the pre- (M=4.27, SD=1.74) and post-test [M=6.22, SD=3.13, t(17)=-3.39, p=.004]. The eta squared statistic (.40) indicated a large effect size. Additionally, considering the small sample size used in the experiment and the fact that the normality assumption was not fullfilled, and additional non-parametric test was performed to further validate the result. A Wilcoxon Signed-rank test showed that there was a significant increase between pre- and post-test (Z = -2.65, p = 0.008).

A one-way between-groups analysis of covariance was conducted to compare the effectiveness of the two different platforms. The independent variable was the type of intervention (multiple mice game, augmented reality game), and the dependent variable consisted of scores on the post-test administered after the intervention was completed. Participants' scores on the pre-test were used as the covariate in this analysis. Preliminary checks were conducted to ensure that there was no violation of the assumptions of linearity, homogeneity of variances, homogeneity of regression slopes, and reliable measurement of the covariate. After adjusting for pre-test scores, there was no significant difference between the two intervention groups on post-test scores [F (1,42)=2.82, p=.1, partial eta squared=.065].

Considering the fact that the normality assumption was not fulfilled for the multiple mice pre-test scores, additional non-parametric tests were performed to further validate the result. A Mann-Whitney U test was performed on the delta between pre- and post-test for both groups (delta = post – pre). The test showed that there was no significant difference between the delta values of both groups (Z = -1.60, p = 0.11). A rank-transformed ANCOVA was also performed, in which the results of the pre- and post-test of both groups were first transformed into ranks. After adjusting for pre-test ranks, there was no significant difference between the two intervention groups on post-test ranks [F (1,42)=3.65, p=.063, partial eta squared=.082].

A 2 by 2 between-groups analysis of covariance was conducted to assess the effectiveness of the two platforms for male and female participants. Considering the small number of sub-groups, instead of using directly the pre- and post-test, rank transformations were performed on both sets of values. The independent variables were the type of videogame (augmented reality, multiple mice) and gender. The dependent variable was the ranks of the post-test. Ranks on the pre-test were used as a covariate to control for individual differences. Preliminary checks were conducted to ensure that there was no violation of the assumptions of normality, linearity, homogeneity of variances, homogeneity of regression slopes, and reliable measurement of the covariate. After adjusting for pre-test ranks, there was no significant interaction effect [F (1,40)=2.32, p=.136]. These results suggest that it cannot be concluded that males and females responded differently to the two versions of the videogame.

Experiment N°3: Third iteration of the videogame, Chapter IV

The third and final experiment was performed after the third iteration of the videogame was completed, in May 2011. The goal of this first experiment was two-fold: first, to compare this final version of the game with the original one; and second, to understand the importance of the fantasy element of the game.

Sample Description

The first experiment was performed with 12^{th} grade students of school A, the same school were the first experiment was performed. All the students that participated in the experiment belonged to the same class, which corresponded to the scientific/mathematic class of school A. From all the students of that class 36 were randomly selected to participate in the study, 27 male and 9 female. The 36 selected students were further randomly subsampled into two groups: one group of 20 students to play the fantasy version of the videogame, and one group of 16 students to play the non-fantasy version of the videogame.

Experimental Setup

The experiment was carried out in five different sessions, three with the students that played the fantasy version, and two with the students that played the non-fantasy version, each session with duration of 2 hours. All the sessions were performed in the same classroom of school A.

In every session, the same researcher accomplished the role of the teacher. Also in every session, the same script was used. Both versions of the videogame only differed in the fantasy aspect, which included the background story and the visual aesthetics.

Each session had the following structure:

- Students answered the conceptual survey of electrostatics (Appendix A) and a questionnaire detailing their previous experience with technology and videogames (30 minutes).
- The 9 students were randomy assigned in three groups of three students. One of the researchers takes the role of the teacher and follows the class script. Throughout the session, students play the different individual levels of the videogame first and then the collaborative levels with their respective groups (1 hour).
- Students answered the conceptual survey of electrostatics (Appendix A) (30 minutes).

Results and Statistical Analysis

The results of the conceptual evaluation pre- and post-tests showed an increase in the average number of correct answers from 7.36 to 12.36, with standard deviations of 2.69 and 3.77 respectively, for the whole sample that participated in the experiment (including both fantasy and non-fantasy versions). A Kolmogorov-Smirnov test of normality was performed on both pre- and post-test results, and in both cases the normality assumption was fullfilled.

A paired-samples t-test was conducted to evaluate the impact of the intervention on scores on the conceptual survey. There was a statistically significant increase in scores comparing the pre- ($M=7.36$, $SD=2.69$) and post-test [$M=12.36$, $SD=3.77$, $t(35)=-8.78$, $p<.0005$]. The eta squared statistic (.68) indicated a large effect size.

Considering the small sample size used in the experiment, and additional non-parametric test was performed to further validate the result. A Wilcoxon Signed-rank test shows that there is a significant increase between pre- and post-test ($Z = -4.91$, $p < 0.0005$).

To compare the effectiveness of this final version with the original one, a one-way between-groups analysis of covariance was conducted. The independent variable was the type of intervention (original version, final version), and the dependent variable consisted of scores on the post-test administered after the intervention was completed. Participants' scores on the pre-test were used as the covariate in this analysis. Preliminary checks were conducted to ensure that there was no violation of the assumptions of linearity, homogeneity of variances, homogeneity of regression slopes, and reliable measurement of the covariate. After adjusting for pre-test scores, a significant difference was found between the two intervention groups on post-test scores [$F(1,60)=4.55$, $p=.037$, partial eta squared=.071].

To compare the effectiveness of this final version with the original one, a one-way between-groups analysis of covariance was conducted. The independent variable was the type of intervention (original version, final version), and the dependent variable consisted of scores on the post-test administered after the intervention was completed. Participants' scores on the pre-test and the frequency of playing videogames were used as the covariate in this analysis. Preliminary checks were conducted to ensure that there was no violation of the assumptions of linearity, homogeneity of variances, homogeneity of regression slopes, and reliable measurement of the covariate. After adjusting for pre-test scores, a significant difference was found between the two intervention groups on post-test scores [$F(1,60)=4.30$, $p=.042$, partial eta squared=.068].

Regarding the sub-experiment focused on the fantasy component of the videogame, a one-way between-groups analysis of covariance was conducted to compare the effectiveness of the two different versions. The independent variable was the type of intervention (fantasy, non-fantasy), and the dependent variable consisted of scores on the post-test administered after the intervention was completed. Participants' scores on the pre-test were used as the covariate in this analysis. Preliminary checks were conducted to ensure that there was no violation of the assumptions of linearity, homogeneity of variances, homogeneity of regression slopes, and reliable measurement of the covariate. After adjusting for pre-test scores, there was no significant difference between the two intervention groups on post-test scores [$F(1,32)=0.61$, $p=.806$, partial eta squared=.002].

A Kolmogorov-Smirnov test of normality was performed on both subgroups (fantasy and non fantasy) for their pre- and post-test results, and in both cases the normality assumption was not fullfilled. Considering this fact, additional non-parametric tests were performed to further validate the result. A Mann-Whitney U test was performed on the delta between pre- and post-test for both groups (delta = post – pre). The test showed that there was no significant difference between the delta values of both groups ($Z = -0.083$, $p = 0.93$). A rank-transformed ANCOVA was also performed, in which the results of the pre- and post-test of both groups were first transformed into ranks. After adjusting for pre-test ranks, there was no significant difference between the two intervention groups on post-test ranks [$F(1,32)=0.057$, $p=.812$, partial eta squared=.002].

To analyze the possible differences in engagement between both versions, Mann-Whitney U test were performed on the resulting score of each of the 7 dimensions of the GEQ: competence, immersion, flow, tension, challenge, negative affect and positive affect. The tests showed that was no significant difference in all dimensions.